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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PALYNOLOGY IN SOUTHERN NORTH AMERICA

INTRODUCTION AND ACKNOWLEDGMENTS

BY PAUL B. SEARS

The present series of papers is an outgrowth of studies begun before 1920 on a reconstruction of the vegetation of Ohio at the time of European settlement. These studies (Sears, 1925–1926) showed the presence of prairie enclaves within a predominantly deciduous forest region. Gleason (1923, p. 84) had meanwhile suggested that prairie and plains species in the Middle West were relicts of a "xerothermic" period of post-glacial climate dryer and warmer than the present. Such an interval had been identified in the European sequence by several lines of evidence and was eventually established for northern Ohio by means of pollen analysis of peats and marls (*Cf.* Sears, 1932, p. 5), as follows:

Northern Ohio Vegetation	European Equivalents (?)	Moisture	Temperature
(1) Record disturbed	.....	.....	Warming
(2) Beech-maple	Subboreal	Humid	Cool
(3) Oak-hickory	Sub-Atlantic	Dry	Warm
(4) Hemlock-beech-pine	Atlantic	Humid	Cool (U. S.)
(5) Pine	Boreal	Dry	Cool
(6) Spruce	Preboreal	Humid	Cold

Both in Europe and North America difficulty was met in applying this sytem as a general pattern of "post-glacial" climatic history. Auer (1930), whose pollen profiles were among the first to be published for North America, strained his interpretation to fit southeastern Canada into the classical European sequence. A re-examination of his results shows three, rather than five, major climatic periods. On the other hand, unpublished work by L. R. Wilson shows for central Ohio more alternations than are found in northern Ohio. In general, the number tends to decrease northward from the extreme limits of Wisconsin glaciation.

Flint, *et al.* (1945) and Flint (1947) made it clear that the term "post-glacial" is relative and not absolute, if indeed it should be used at all. The final retreat of the Wisconsin ice has been a series of retreats, alternating with re-advances of decreasing intensity. One has only to assume that moist climates have been associated with glacial nourishment and dry with ice wastage to understand how the pollen sequence can reflect glacial activity. The number of climatic oscillations recorded in a given sedimentary column should vary with position, becoming fewer as one approaches the present ice limits (Sears, 1948, p. 331).

The question then arises—how far beyond the margin of continental glaciation were the climatic episodes of the Pleistocene registered? If registered in sediments not interrupted by the presence of ice, presumably the record of Pleistocene climate could be carried backward and downward in detail. These conditions have been met by the lacustrine sediments beneath Mexico City (*Cf.* Deevey, 1944).

Study of the climatic record in this basin began in 1948 with the generous collaboration of Mexican colleagues as acknowledged in the first paper of this series (Sears, 1952, p. 242). That paper, confined to a study of the archeological horizons, presented evidence that the lake margin cultures, Archaic (2500–500 B.C.) and Nahua (900–1500 A.D.), were separated by an interval of dry climate, during which the intervening highland culture Teotihuacan (500 B.C.–900 A.D.) became dominant. More precisely a moist period marked by dark humus soil and high lake level initiated the Archaic which persisted into a subsequent dry interval to a time of minimum lake level around 500 B.C. Then began the upland Teotihuacan culture, probably using ground water from the forested slopes above and lasting into the ensuing moist

period. During this period heavy soil erosion and probably deforestation also acted to offset the benefit of increasing moisture. The center of activity returned to the shores of the replenished lakes in the basin floor about 800–900 A.D., during the most recent period of glacier building in the far North. Theoretically, the preceding dry period of the Late Archaic should correlate with ice wastage or retreat at the time spruce forests became established in Alaska during the thermal maximum there for which there is a radiocarbon date of 3500 ± 250 (Heusser, 1953, p. 639).

The still earlier moist climate associated with dark soil and the earliest Archaic culture as determined by Carbon-14 and archeological dating occurred 2500–3000 B.C. This should represent a time of ice accumulation resulting in readvance, or at least arrested retreat, in the northern part of the continent and at high altitudes. Knowledge of glacial history in Canada in the interval between the Mankato and latest glaciations is not sufficient to warrant any geographical designation. The term Cochrane has been used, but no satisfactory evidence of a readvance has been found there.

The 1948 study, extending to a depth of 8 m, encountered still another dry period below the Early Archaic moist level, doubtless representing the Mankato retreat. Thus the record is continuous and apparently consistent with the sequence from northern Ohio. This record overlaps with the truncated upper portion of the deep profiles considered in the papers which follow, giving an uninterrupted stratigraphy up to present time.

Since 1948 material from deep precision cores in the lake sediments under Mexico City has been available, as well as washings at 10-foot intervals from a 200-foot core at Valle Grande in northern New Mexico. Preliminary analysis (Sears and Clisby, 1952) showed sufficient similarity in the two widely separated regions, both beyond the glacial border, to prove that climatic alternations during the Pleistocene were of continental scope. About 300 feet of a 645-foot core from the San Augustin Plains in western New Mexico have also been analyzed, confirming our present results and extending the record well into the last interglacial period.

The papers which follow deal in detail with two cores from Mexico City, Bellas Artes 75 m and Madero 69 m (Zeevaert, 1952). The two pollen profiles, while not equally detailed, are in general agreement. Professor Foreman's thorough study of these sediments contributes much to the complex history of the Cuenca de Mexico and has been indispensable in the interpretation of the pollen profiles. It has not only served as a check on climatic conditions but, by revealing periods of rapid sedimentation, has also explained intervals of low pollen concentration.

Major advances and retreats of the Wisconsin or Fourth Glacial have been identified with long gradients of temperature and moisture change. Both the major advances and retreats are characterized by secondary phases of advance and retreat, advance being indicated by periods of moist vegetation, retreat by dry. Paradoxically, moist periods appear to be times of rising temperature. However, this is understandable since their maxima are inversely proportional to the intensity of glaciation and since Mexico lies within the Tropics.

The dry phases of secondary or minor retreat apparently varied in temperature. The latest, in progress since about 1750 A.D. (Lawrence and Elson, 1953, p. 89; Faegri, 1948, p. 293), is a time of increasing warmth. How long it may continue is a question of considerable practical importance. It has already resulted in marked biological changes. Similar changes in the past have endured for centuries, and the first paper of this series has shown that such changes have notably affected human activity (Sears, 1952).

While our climatic interpretations rest chiefly upon changing proportions of upland forest pollen, the nonforest pollen is also significant. Certain herbs become abundant after destruction of forest by tectonic, volcanic or human activity. Again, pollen of early Wisconsin age has been identified by Professor Barghoorn and Miss Wolfe as that of maize, which indicates that this plant long antedates human cultivation of it (Barghoorn, *et al.*, 1954, p. 239).

This project has involved the collaboration of engineer, geologist, sedimentologist, pollen analyst, ecologist and archeologist. In turn, information of intrinsic interest to each group, as well as to the climatologist and plant geographer, has been obtained. Enough has

been learned of the characteristic pattern of climatic recurrences over a substantial portion of time to merit further work of this type for appraising future trends.

To supplement acknowledgments made elsewhere in this series, our deep obligation for financial assistance from the Geological Society of America, The Wenner-Gren Foundation, and the National Science Foundation and for transport facilities from the Willys-Overland Company must be expressed. We are also indebted to Oberlin College, Harvard University and the Seminario para Estudios Cenozoicos of the Instituto Geologica for generous facilities and staff collaboration. Without the precise engineering skill and scientific enthusiasm of Dr. L. Zeevaert who furnished the cores, our study would not have been possible. For the writings of the late Kirk Bryan (1948) and Ing. A. R. V. Arellano (1951), as well as for their encouragement and active personal assistance, our gratitude is a continuing one, as it is to Dr. Pablo Martinez del Rio for his initial suggestion that the Mexican pollen record be studied. New perspective has been given to the problem of the origin of maize through the interest of Professor Mangelsdorf and the subsequent morphological work of Professor Barghoorn and Miss Wolfe. The abundant diatom material is now being worked over by Dr. Ruth Patrick, while the ostracod fauna still awaits study.

The author of this introduction would be gravely remiss if he failed to pay especial tribute to the loyalty, persistence and competence—both technical and intellectual—of his immediate partners in this latest phase of a study which has extended through three decades. *Sine sociis, nemo vincit.*

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PALYNOLOGY IN SOUTHERN NORTH AMERICA

PART II: STUDY OF TWO CORES FROM LAKE SEDIMENTS OF THE MEXICO CITY BASIN

BY FRED FOREMAN

ABSTRACT

Two cores taken from near the center of Mexico City are each divisible into seven zones; the division is based on differences in texture, biota, waterholding capacity, and stratigraphy. Zones of the same number in each of the cores are similar in nearly all respects.

The lake and its surrounding basin are in the same physiographic and climatic province, and the rocks of the basin are consanguineous and are either pyroclastics or flows. Rocks in the Mexico City basin are predominantly glassy or hypocrystalline; many are vesicular and subject to rapid weathering and generally are easily eroded. Sediments derived from these rocks are rather sensitive indicators of variations in climate. Throughout the time sedimentation was taking place in the lake there were in this region many volcanic eruptions, and some tectonic activity, and these too have affected the vegetation and lake sediments, which include clays, fresh to weathered particles of ash and clastics from the flows, and authigenic, chemical, and organic deposits as well as pollen and plant fragments. A tentative history is given of the climates, volcanism, and tectonic activity in this area during the time represented by the sediments.

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INTRODUCTION

The use of fossil pollen as an indicator of post-Pleistocene climates has become common in both Europe and North America, and some work has been done with the pollen from sediments that are Pleistocene or older. Fossil pollen found in lake or swamp sediments is regarded as representative of the vegetation in the immediate area. Most postglacial sediments are in kettles and other ice-formed depressions. The very process which made these basins, however, has limited the formation of pollen-bearing sediments to post- or interglacial de-

posits. Thus there is always a hiatus in the pollen record in glaciated areas between interglacial deposits of different stages. It is therefore necessary to go outside the glaciated regions to find a continuous record of Pleistocene pollen deposition.

Undrained as well as drained basins are rare outside the glaciated areas and sediments of such basins that are continuous and also pollen-bearing are still rarer. Most favorable basins are in areas of high relief where recent tectonic or volcanic activity or both have formed suitable depressions. The sediments in these basins will differ from those of peat bogs. The introduction of pyroclastics through volcanism and the destruction of plant life by the ejectamenta are variables that must be considered for correct interpretation in relation to the time involved and pollen content.

The Mexico City basin contained a lake from at least the beginning of the Pleistocene. Into this lake were carried not only the usual allogenic sands, silts, and clays of weathering and erosion, but also large amounts of volcanic ash. Some of this ash was carried by the wind directly to the lake, but most of it was deposited for a shorter or longer time either within the drainage basin or was wind borne from aeolean deposits outside the basin. Mixed with these deposits is pollen of the vegetation surrounding the lake as well as authigenic fossils and lake sediments.

This study was made to procure recognizable evidence of past climates, volcanism, and tectonic activity. It was also an attempt to learn whether the record of sedimentation would be of use to the paleobotanist and paleoclimatologist.

Acknowledgments

The writer is indebted and grateful to Professor Paul B. Sears for making funds available for this work, to Dr. Arellano for his advice and guidance in the field, to Professor Paul F. Kerr for the use of the differential thermal analysis apparatus at Columbia University, to Dr. Zeevaert for making available samples from his cores and for the use of his data on the waterholding capacity of the sediments, to Mrs. K. Clisby for advice and enthusiastic co-operation, and to Miss Alice Johnson for kind and pertinent editorial help in the preparation of this manuscript.

Method of Study

The specimens studied were from two cores drilled near the center of Mexico City by Dr. Zeevaert, who logged the cores and obtained the water content as a percentage of the dry weight of solids present. Bellas Artes, from which the core 80 was taken, is immediately east of the Alameda, the Central Park of Mexico City; the 57–Madero core was taken approximately 250 m to the southeast of the Bellas Artes site. Thus both cores are from the very central part of the city.

These two cores give two vertical linear series of samples, and since the cores are less than 300 m apart the scope of investigation is very limited. The cores are continuous, but the samples taken from them are not; they were chosen from parts which might contain plant pollen, or which showed interesting phases of sedimentation. The 57—Madero core averages about two samples to the meter, or one to every 20 inches, and since they are small they cover about 10 per cent of the actual stratigraphic sequence of the core. In the 80-Bellas Artes core the samples are larger, but, except for the last 12 m, they are approximately one to the meter, again covering about 10 per cent of the length of the core. The lower part, 63.40–74.90 m, has about three times as many samples per meter as the upper part, or about 30 per cent of the core.

Many phases of the sedimentation are absent, as is obvious from Zeevaert's log of the core, but the samples do represent most of the sediments in the lake, except for several thin white or brown volcanic ash layers which were purposely omitted but which appear in Zeevaert's logs. Many of these samples have a very high water content, the weight of water often being two to three times that of the solids.

The degree of hydration of the ash and the amount of clay in the sediment are the prime reasons for high water content. This is in most places but not everywhere related to fineness of texture. There are many ash and some diatom layers which have fine texture but low water content; in these horizons the ash is fresh and the diatoms are without much clay

and weathered ash. As might be expected, the water content of the sand zones is low; this is adequately explained by their coarser texture and the general absence of much weathering.

Water content is highest in the fine, clayey, well-weathered ash in which sapropel is common and when wet, these samples are gel-like and structureless.

No bedding planes are apparent except in a very few samples, so this feature could not be used in estimating the amount of possible mixing; but irregular changes in color, texture, and kind of material in some of the samples indicate some mixing which, however, probably does not affect the interpretation appreciably.

It is not possible or necessary to interpret these samples individually or even each of the cores separately, but they will be grouped in naturally occurring units of sedimentation. Tables 1 and 2 outline the amount of carbonate, type and frequency of the authigenic fossils, the structures, the mineral species and their frequency, and the water holding capacity of the samples of the Madero and Bellas Artes core respectively. The allogenic fossils, the plant pollen, were not identified but are treated in detail in another paper of this series by K. H. Clisby. Detailed petrographic description of the Bellas Artes core is presented in Table 3, and textural analyses of some of these samples in Table 4. A generalized summary of the sedimentation and interpretation of conditions under which deposition occurred is shown in Table 5.

The 80—Bellas Artes samples were placed in round glass containers, 2 inches in diameter by 2 inches deep, with tin screw tops. When dry, the samples weighed about 50 grams. Samples from 57—Madero were chosen especially for pollen analysis and were very small for sedimentary analysis. They were in glass vials and when dry, weighed from about 1 to 5 grams.

The samples were first examined under a stereomicroscope, and an initial evaluaton of texture, composition, and structure was made as well as a qualitative test for carbonate by use of dilute HCl. A systematic petrographic and textural study followed. Minerals were identified by standard procedures by use of petrographic microscope. Optical constants were determined by immersion oils after Larsen and Berman (1934). The oils up to N. 1.68 were standardized by a Zeiss refractometer and above that with the hollow prism method by use of a sodium vapor lamp.

Mechanical analyses on the Bellas Artes samples were made, using standard Tyler sieves for sand-size and larger particles and pipette analyses supplemented by microscope measurements for silt and clay sizes. For many of the weathered samples the distribution was in part a function of the energy used in sieving or in stirring before pipetting. Data are not given from samples where this affected the size distribution noticeably.

Frequency of mineral and fossil species was determined by quartering down with an Otto microsplit to suitable size groups and counting either under the petrographic microscope or the steromicroscope depending on the size of the particles. Both indirect (alkalimeter) and direct (absorption by ascarite) determinations were made by standard procedures for the carbon dioxide. The alkalimeter method was used only for those samples obviously high in carbon dioxide.

Tests for the SO_4 and Cl ions were made by heating one gram of sediment in about 90 cc of water for three hours; then more water was added to make 100 cc. This was allowed to stand, and then two filtered aliquot portions of 10 cc each were taken. One of these was tested for chlorine ions by use of silver nitrate and the other for sulphate ions by barium chloride. The precipitate was compared to standard solutions carrying 1, ½, ¼, ⅛, and 1/16 per cent by weight of chlorine and 2, 1, ½, ¼, ⅛ per cent by weight of sulphate as standards. The 1/16 per cent for chlorine and ⅛ per cent for sulphate were the lowest limit on which observations could be made. Fresh comparison solutions were made for each run, and the silver chloride was kept away from light except when comparison was being made with the unknown.

Color determinations were made using Rock Color Chart of 1948. Light from a north window was used, between 11 a.m. and 4 p.m., on dry samples on a white porcelain background. Comparison with wet samples showed

TABLE 1.—MEXICO 80—BELLAS ARTES CORE

V.A.—Very Abundant, greater than 20%
A.—Abundant.....10–20%
F.—Frequent..... 5–10%
O.—Occasional..... 1–5%
R.—Rare.....less than 1%
c.—Circular or disklike.....
l.—Elongate or lens-shaped.....

Depth (Meters)	Description of sample	CO_3%	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quartz	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in per cent dry weight solids (After Zeevaert)
3.60–3.80	Light-yellowish-brown, porous, crumbly, sandy weathered ash	7.3	O	O	R.c.l.	..	F	O	R	F	F	..	R	R	60
4.40–4.60	Yellowish-brown, crumbly, sandy weathered ash	4.2	F	.....	O.l.	..	..	O	R	F	F	..	R	..	65
5.10–5.20	Yellowish-brown, porous friable, sandy weathered ash	5.0	F	O	O.c.	R	..	R	..	O	O	..	..	R	65
5.7–5.9	Yellowish-brown, porous, soft ashy marl	22.9	..	.....	...	..	..	..	O	O	..	..	..	..	75
5.9–6.10	Yellowish-brown, soft, porous ashy marl	22.7	..	F	...	..	..	..	..	O	O	..	..	..	65
7.40–7.60	Yellowish-gray, porous, friable, sandy weathered ash	1.5	..	O	O.l.	..	..	R	..	O	O	..	..	..	5
8.60–8.80	Yellowish-gray, rather hard, fine weathered ash	3.5	..	F	R.c.	..	..	..	..	F	O	R	..	R	150
9.00–9.20	Olive-gray, hard, calcareous weathered ash	4.6	..	R	R.c.	R	..	..	..	O	O	..	..	..	275
9.40–9.60	Olive-gray, compact, calcareous weathered ash	4.9	..	O	F.c.	O	..	O	..	O	O	R	..	..	275
9.60–9.80	Light-olive-gray, compact, calcareous, weathered ash	5.4	..	O	F.c.	..	..	O	..	O	O	R	..	..	275
10.00–10.20	Yellowish-gray, fine-grained very hard, calcareous clayey ash	5.8	..	O	F.c.	..	..	R	R	F	O	R	R	..	280
11.00–11.20	Light-olive-gray, fine-grained, clayey ash	4.5	..	.....	F.c.	O	..	..	..	O	R	..	..	..	275
12.80–13.00	2 phases: Yellowish-brown, crumbly, micro-coquina	26.2	..	VA	O	O	..	..	..	..	..	..	..	..	.....
	and olive-gray, dense, rather hard, weathered ash	8.5	..	O	A	F	..	O	..	R	R	..	..	..	235
13.02–13.20	Light-olive-gray, dense, fine weathered ash	4.7	..	O	F.c.	..	..	..	..	R	R	..	..	..	260
14.10–14.60	Micro-coquina lumps and light-olive-gray, porous, friable, clayey fine ash	24.0	..	VA	...	..	..	..	..	..	..	..	..	..	15
		6.7	..	A	A	..	..	..	..	R	R	..	..	..	250
15.8–16.00	Yellowish-gray, fine-grained, hard clayey ash	..	..	O	F.c.	..	..	..	..	R	R	..	..	..	248–350
16.60–16.80	Moderate-olive-gray, porous rather hard weathered ash	5.7	..	F	R.c.	..	O	..	..	R	R	..	..	..	235
17.60–17.80	Light-olive-gray, rather hard weathered ash	2.5	..	F	F.c.	..	..	..	..	R	R	R	..	..	300
18.20–18.40	Light-olive-gray, well-consolidated weathered ash	3.4	..	.....	F.c.	..	..	..	..	O	R	..	..	..	225
19.80–20.00	Olive-gray, fine-grained, rather hard weathered ash	3.0	..	R	O.c.	..	..	O	..	R	R	..	..	..	220
20.40–20.60	Olive-gray, friable, porous, sandy weathered ash	3.7	O	A	F.c.	..	..	..	R	F	R	..	R	R	175
21.60–21.80	Pale-yellowish-brown, friable, calcareous, weathered fine ash	5.0	..	F	F.c.	..	C	R	R	O	O	..	..	..	225

21.80–22.00	Pale-yellowish-brown, consolidated, slightly porous, hard clayey ash	..	..	O	F.c.	..	..	..	..	O	..	..	..	..	225
22.40–22.60	Light-olive-gray, lumpy, porous soil-like weathered ash	3.4	..	O	O.c.l.	O	O	..	..	O	R	..	..	..	150
22.80–23.00	Light-olive-gray, well-consolidated, rather hard, weathered fine ash	3.1	..	O	F.c.	..	..	O	..	O	O	R	..	..	200
23.00–23.20	Olive-gray fine-grained, lumpy, hard, weathered fine ash	2.5	..	O	F.c.	..	..	F	..	O	O	..	..	..	200
24.00–24.20	Light-olive-gray, fine-grained, hard, weathered ash	1.1	..	F	O.c.	..	..	F	..	O	R	..	..	..	250
25.20–25.40	Light-olive-gray, fine-grained, hard, splintery fracture, clayey ash	1.4	..	O	F.c.l.	..	..	F	..	O	R	..	..	..	325
26.20–26.40	Light-olive-gray, unconsolidated, calcareous weathered ash	6.4	..	F	A.c.	O	F	..	..	O	O	..	..	R	50
28.60–28.80	Light-olive-gray, soft, unconsolidated, calcareous weathered ash	9.1	..	A	A.c.	..	..	O	O	F	O	R	..	..	225
29.20–29.40	2 phases: Dark-olive-gray, dense hard clay and light-gray, porous, very soft, coquina	5.8	O	O	O.c.	..	..	F	..	O	R	..	..	..	300
		..	O	A	F.c.	..	..	F	..	O	R	..	..	..	.....
30.40–30.60	Light-olive-gray, weathered ash with patches of ostracod tests	2.4	..	F	F.c.	..	..	O	..	O	O	..	..	..	250
31.00–31.20	Olive-gray unconsolidated calcareous ash	6.5	..	F	F.c.	..	..	O	O	O	O	..	..	..	275
32.12–32.30	Gray, pepper and salt, friable ashy sand	0.9	..	.....	F.c.	..	..	..	R	A	A	R	R	..	150
33.75–33.90	Gray, pepper and salt, friable ashy sand	3.1	..	.....	O.c.	..	O	..	O	A	A	R	R	..	20
34.10–34.20	Light-olive-gray, salt and pepper ashy sand	1.1	..	.....	..	..	..	..	O	A	A	O	R	O	20
35.22–35.40	Yellowish-gray, friable, weathered and unweathered ash	0.5	O	.....	...	..	..	..	..	F	F	R	R	R	25
36.36–36.50	Medium-gray, friable, sandy calcareous ash	8.1	F	F	F.l.	F	..	..	..	F	O	R	R	..	25
37.62–37.82	2 phases: Light-gray, pepper and salt and dark-gray; both friable, sandy ash	1.5	..	F	O.c.l.	..	..	..	..	O	R	..	..	..	100
		..	..	O	O.c.l.	..	..	O	..	R	R	R	R	..	.....
38.21–38.40	Light-olive-gray, fairly hard, weathered ash	1.9	O	F	F.c.l.	F	..	O	..	R	R	..	..	..	175
39.10–39.20	Light-olive-gray, hard, weathered ash	0.4	..	O	O.c.l.	F	..	F	..	O	O	..	..	..	225
40.90–41.10	Light-yellowish-gray, unconsolidated sandy ash	..	..	A	A.c.	A	..	F	..	R	R	..	..	..	230
41.90–42.16	Light-olive-gray, well-consolidated, weathered ash	0.2	..	O	F.c.l.	F	..	O	..	O	R	..	..	..	220
42.80–43.0	Yellowish-gray, friable, calcareous, sandy ash	14.6	A	A	F.c.l.	O	..	O	..	O	R	R	R	..	200
43.40–43.60	Light-olive-gray, dense, calcareous, weathered fine ash	9.3	..	F	O.c.	..	..	..	..	O	O	..	..	..	90
43.98–44.17	Light-olive-gray, porous, rather soft, weathered ash	3.0	..	F	F.c.	F	..	O	..	O	O	R	R	..	175
44.17–44.36	Light-olive-gray, lumpy, calcareous, sandy weathered ash	7.8	..	F	F.c.	F	..	O	..	F	O	..	..	..	25
45.12–45.31	Light-olive-gray, porous, rather hard, silty, weathered ash	2.5	..	O	F.c.	O	..	O	..	O	R	..	..	..	125

TABLE 1.—*Continued*

Depth (Meters)	Description of sample	CO_2%	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quartz	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in per cent dry weight solids (After Zeevaert)
46.80–47.00	Yellowish-gray, pepper and salt gray mixture of slightly weathered sandy ash	..	..	.....	O.c.	..	..	..	O	A	F	..	R	..	30
47.20–47.40	Light-olive-gray, slightly weathered, sandy ash	..	..	.....	O.c.	..	..	..	O	A	A	..	R	..	40
48.40–48.65	Light-olive-gray, friable slightly weathered, sandy ash	..	..	.....	R.c.	R	..	..	O	A	A	R	R	O	30
49.92–50.40	Light-olive-gray, lumpy, friable, slightly weathered sandy ash	..	..	.....	...	..	..	..	R	A	A	R	R	R	20
51.00–51.20	Yellowish gray, unconsolidated sand	..	..	.....	O.c.	O.c.	..	..	O	VA	A	O	R	O	20
52.27–52.37	Olive gray, very friable ashy sand	..	..	.....	...	..	R	..	O	A	F	R	R	..	15
52.37–52.55	Light-olive-gray, unconsolidated sandy ash	..	..	.....	...	..	..	..	..	F	O	R	R	..	15
53.54–53.72	Light olive-gray, unconsolidated, sandy ash	..	..	.....	...	..	..	..	O	A	F	R	R	O	25
56.80–57.00	Yellowish-gray, unconsolidated sandy ash	..	..	O	O.c.	..	O	O	F	F	O	R	R	..	25
58.80–59.05	Olive-gray, readily friable, ashy sand, somewhat weathered	..	..	....	R.c.	..	O	..	..	A	F	R	R	..	20
59.90–60.05	Olive-gray, unconsolidated ashy sand	..	..	.....	...	..	..	..	O	A	F	R	R	O	15
60.80–61.00	Olive-gray, unconsolidated ashy sand	..	..	.....	...	..	..	..	F	A	F	R	R	R	20
61.80–62.00	Olive-gray, unconsolidated weathered sandy ash	..	..	R	O.c.l.	..	O	O	R	O	O	..	..	..	75
63.40–63.60	Light-olive-gray, porous ash, slightly weathered	0.6	..	....	O.c.	O	O	O	..	F	O	..	..	..	100
63.60–63.80	Light-olive-gray, porous ash, weathered and unweathered	0.8	..	R	F.l.	..	O	O	..	O	O	..	..	..	100
64.00–64.20	Light-gray consolidated but porous fine ash	1.0	..	.....	F.c.	..	..	O	R	F	F	..	R	R	40
65.25–65.40	Light-olive-gray, hard fine weathered ash	..	..	....	O.c.	A	..	..	..	O	R	R	..	R	175
65.85–66.00	Light-olive-gray, unconsolidated weathered fine ash	..	..	R	O.c.	..	..	..	R	F	O	R	R	R	40
67.68–67.80	Gray, friable, fine, fresh and altered ash	..	..	.....	F.c.	F	..	..	..	F	O	..	..	..	100
67.80–68.00	Olive-gray, compact, but friable weathered ash	..	..	.....	...	..	..	..	..	O	O	..	..	..	25
68.40–68.60	Light-olive-gray, friable, somewhat weathered ash	..	..	.....	O.c.	O	..	..	..	F	F	..	..	R	30
68.90–69.10	Gray, compact, hard, slightly weathered ash	..	..	.....	...	O	..	..	..	F	O	..	..	..	200
69.10–69.30	Light-olive-gray, compact, rather hard, weathered ash	..	..	.....	O.c.	O	..	..	..	O	O	..	..	..	220
69.30–69.50	Light-olive-gray, compact, hard, sandy, weathered ash	..	..	.....	O.c.	O	..	..	..	A	F	..	R	R	240
69.50–69.70	Olive-gray, rather hard, slightly weathered ash	..	..	.....	R.c.	F	O	..	R	O	O	..	..	R	225
69.70–69.90	Light-olive-gray, compact, fine slightly weathered ash	..	..	.....	F.c.	F	..	..	..	O	O	..	..	..	200
69.90–70.10	Light-olive-gray, rather hard, slightly weathered ash	..	..	.....	O.c.	O	..	O	R	O	O	..	..	..	175
70.10–70.30	Light-olive-gray, friable, weathered ash	..	..	.....	F.c.	F	..	..	..	O	O	..	..	..	150
70.30–70.50	Brownish-gray, slightly friable, well-weathered ash	..	..	.....	F.c.	F	..	..	..	F	O	..	..	..	75
70.50–70.70	2 phases: olive-gray, sandy friable ash; light-olive-gray, friable ash, both slightly weathered	..	..	.....	O.c.	O	..	..	..	F	F	..	..	..	70
		..	..	.....	F.c.	F	..	..	..	F	F	..	..	..	.....
70.90–71.10	Light-olive-gray, friable, ashy sand	..	..	.....	F.c.	F	..	..	O	A	F	R	R	..	60
71.20–71.30	Dark-yellowish-brown, compact, well-weathered ash	..	..	.....	F.l.	O	O	O	..	F	O	..	..	..	100

TABLE 2.—MEXICO 57—MADERO CORE

V.A.—Very Abundant, greater than 20% O.—Occasional..... 1–5%
A.—Abundant.....10–20% R.—Rare.....less than 1%
F.—Frequent..... 5–10%

Under "Carbonates" the above letters are qualitative, merely indicating the apparent activity of dilute hydrochloric acid on the the dried sample.

In the diatom column "c" = circular appearing or disklike, and "l" = the elongate or lens-shaped diatoms.

Depth (Meters)	Description of sample	Carbonate	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quartz	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in % dry wt. solids (After Zeevaert)	Remarks
3.10	Brownish-gray, compact weathered ash	O	...	....	.....	...	...	...	O	F	O	...	O	R	....	.....
3.30	Brownish-gray, compact weathered ash	A	...	R	O	O	O	O	...	F	O	...	R	...	....	.....
3.50	Brownish-gray, compact weathered ash	F	R	....	O.l.	...	F	O	...	F	O	R	O	...	....	A little fresh pumiceous ash, N 1.505
3.70	Brownish-gray, clayey ash	F	R	....	O.l.	...	F	O	...	F	O	...	R	...	....	.....
3.90	Brownish-gray, compact weathered ash	F	...	.....	R.c.	...	O	...	...	F	O	...	R	...	60	A rare piece of sanidine, rare fresh brown glass, N 1.525
4.10	Brownish-gray, compact clayey ash	R	...	.....	O.l.	...	O	...	R	O	R	...	R	...	60	A little fresh pumiceous ash, N 1.510
4.30	Brownish-gray, porous weathered ash	F	R	....	O.l.	...	O	O	...	F	O	R	O	...	65	A little fresh pumiceous ash, N 1.505
4.50	Brownish-gray, clayey ash	F	...	.....	F.l.	...	O	O	...	O	O	...	R	...	60	Much fresh pumiceous glass, N 1.505
4.70	Brownish-gray, compact weathered ash	A	O	....	O.l.	...	O	...	...	O	O	...	R	...	65	Few fragments of pelecypod shell, a little fresh ash
4.90	Brownish-gray, clayey ash	O	O	R	O.l.	...	...	R	...	O	O	...	R	...	75	A little fresh pumiceous ash, N 1.510
5.10	Brownish-gray, weathered ash	O	R	R	O.l.	...	...	R	R	O	O	...	R	...	80	A little fresh pumiceous ash
5.20	Brownish-gray, compact, clayey ash	O	O	R	.....	...	O	...	...	F	F	...	O	...	80	Much brown to black fresh glass, N 1.530

TABLE 2.—*Continued*

Depth (Meters)	Description of sample	Carbonate	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quartz	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in % dry wt. solids (After Zeevaert)	Remarks
5.40	Brownish-gray, crumbly marl and weathered ash	A	O	....	O.l.	...	...	...	...	F	O	...	R	...	85	Rare pumiceous clear glass, N 1.510
5.60	Brownish-gray, lumpy, friable marl and weathered ash	A	O	O	.....	...	R	...	...	O	R	...	...	...	70	.....
5.80	Brownish-gray, clacareous clayey ash	A	R	R	.....	...	...	R	...	...	...	...	...	...	60	Some small gypsum crystals
6.00	Brownish-gray with white patches; white, almost pure calcite; gray, calcareous clayey ash	A	R	....	.....	...	...	...	...	R	...	...	...	...	90	.....
6.20	Light-brownish-gray, marly coquina and weathered ash	A	...	VA	.....	...	...	...	...	O	O	...	...	...	....	Rare glassy ash, N 1.525
6.40	Pale-yellowish-brown, marly coquina and weathered ash	A	...	VA	.....	...	...	...	...	O	O	...	...	...	110	Rare glassy ash, N 1.525
6.60	Yellowish-brown, calcareous sandy ash	A	...	O	.....	...	...	...	...	A	F	...	R	...	100	.....
6.80	Light-olive-gray weathered ash and fresh basalt ash	A	...	F	.....	...	...	...	...	F	F	...	O	...	90	Much fresh brown basalt glass, N 1.538
7.00	Light-olive-gray, friable marl and weathered ash	A	...	F	O.l.	...	...	...	...	O	O	...	R	...	60	Rare, fresh, glassy ash, N 1.520
7.40	Light-olive-gray, friable weathered ash	F	...	F	.....	...	...	...	...	O	R	...	...	...	80	.....
7.85	Light-olive-gray, porous, friable oolite-marl and weathered ash	A	A	F	.....	...	...	...	...	O	R	...	...	...	50	Much fresh basaltic glass, N 1.535
9.37	Light-olive-gray, compact, sandy weathered ash	F	...	....	F.c.	...	...	...	F	O	O	...	R	...	260	Few chalcedony grains; some fresh ash
9.56	Light-olive-gray, compact, clayey ash	F	...	F	F.c.	...	...	O	...	R	R	...	...	...	240	.....
9.93	Light-olive-gray, hard, clayey ash	F	...	....	F.c.	...	...	...	...	R	R	...	...	...	350	.....
10.31	Light-olive-gray, diatoms, ostracods and weathered ash (micro-coquina)	A	...	A	A.c.	...	...	...	R	R	R	...	...	...	300	.....
11.00	Light-olive-gray, weathered ash	O	...	O	F.c.l.	...	...	...	...	O	O	...	O	...	300	.....
11.20	Light-olive-gray, weathered ash	O	...	O	F.c.l.	...	...	...	...	O	R	...	...	...	350	.....
11.60	Light-olive-gray, friable, clayey ash	O	...	F	F.c.	...	...	...	...	O	R	...	...	...	310	Rare brown fresh basalt glass; a few grains of chalcedony
13.07	Yellowish-brown, hard, clayey ash	R	...	O	F.c.	...	A	O	...	O	R	...	...	...	250	Rare fresh glass, N 1.510

13.07	Yellowish-brown, hard, clayey ash	R	...	O	F.c.	...	A	O	...	O	R	...	...	...	250	a few grains of chalcedony Rare fresh glass, N 1.510
13.64	Brownish-gray, hard clayey ash	...	...	...	O.c.	...	A	...	...	R	R	...	...	...	300	.....
14.02	Light-olive-gray, friable sandy, weathered ash, many Ostracod tests	F	...	A	O.c.	...	O	...	...	F	O	O	O	...	240	.....
14.21	Light-olive-gray, porous, hard, clayey ash	F	...	O	F.c.	...	O	...	R	O	O	R	...	...	310	Rare fresh black volcanic glass, color due to inclusions, N 1.520
15.07	Light-olive-gray, porous, friable, clayey ash and fossils (sub-coquina)	A	...	A	F.c.	...	...	O	R	R	...	R	R	...	225	.....
15.45	Light-olive-gray, porous, hard, weathered ash	A	...	A	O.c.	...	O	O	...	F	R	...	R	...	200	.....
16.21	Yellowish-gray, porous, friable, weathered ash	F	...	O	F.c.	...	...	...	...	O	R	...	...	...	200	.....
17.20	Light-olive-gray, compact, hard clayey ash	O	...	O	F.c.	...	...	O	...	O	R	...	O	...	275	.....
17.43	Light-olive-gray, porous, hard clayey ash	R	...	O	O.c.	...	...	...	...	O	R	...	...	...	320	.....
17.86	Salt-and-pepper-gray, porous, clayey ash and ostracods	A	...	A	.....	...	O	...	...	O	O	R	...	...	300	.....
18.29	Light-olive-gray, compact, clayey ash	F	...	F	R.c.	...	...	O	...	O	R	...	R	...	280	Rare fresh black volcanic glass, N 1.510
18.53	Light-olive-gray, compact, clayey ash	R	...	...	O.c.	...	...	O	...	O	...	R	...	...	325	A few specks of pyrite
19.34	Light-olive-gray, friable, clayey ash	F	...	O	F.c.	...	...	...	...	F	F	...	O	...	210	A few specks of pyrite, some irregular opaline material
19.37	Light-olive-gray, weathered ash	A	...	O	F.c.	...	F	...	...	O	O	...	...	...	250	Specks of pyrite
19.55	Light-olive-gray, compact, calcareous	A	...	A	O.c.	...	...	...	...	F	O	R	O	...	240	.....
20.39	Light-olive-gray, clayey ash	O	...	O	F.c.	O	...	...	...	O	O	...	R	R	130	.....
21.37	Light-olive-gray, hard clayey ash	F	...	O	O.c.	...	...	...	...	O	R	R	...	...	225	.....
21.56	Olive-gray, porous, crumbly, weathered ash	A	F	A	O.c.	...	...	...	...	F	O	R	R	...	125	Some opaline grains of geyserite
21.75	Olive-gray, crumbly, clayey ash	F	...	F	F.c.	...	...	...	...	O	O	...	O	...	250	.....
22.13	Light-olive-gray, porous, crumbly weathered ash	A	...	A	O.c.	...	...	...	...	O	R	R	...	...	250	A few grains of olivine
22.51	Light-olive-gray, porous, rather hard, clayey ash	F	...	F	O.c.	...	...	...	...	O	O	...	R	...	175	Some white splintery, porous opaline fragments, geyserite
23.64	Olive-gray, porous, crumbly, calcareous, clayey ash	A	...	O	O.c.	...	...	...	O	O	O	R	R	...	150	Quartz, secondary, in small clusters
23.85	Light-olive-gray, porous, crumbly, calcareous, weathered ash	A	...	O	F.c.	...	...	O	...	R	R	...	...	...	200	.....
24.27	Light-olive-gray, compact, rather hard, calcareous clayey ash	A	...	O	F.c.	...	...	O	...	R	...	...	...	...	250	.....
24.63	Light-olive-gray, compact, hard, calcareous, clay	A	...	R	F.c.	...	F	O	R	F	O	...	...	R	260	.....

TABLE 2.—*Continued*

Depth (Meters)	Description of sample	Carbonate	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quartz	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in % dry wt. solids (After Zeevaert)	Remarks
26.13	Light-olive-gray, compact, hard, weathered ash	F	...	R	F.c.	...	...	...	...	O	R	...	...	...	290	.....
26.40	Olive-gray, compact, hard, weathered ash	F	...	R	F.c.	...	...	O	...	F	...	R	...	...	300	.....
26.82	Olive-gray, crumbly, weathered ash	O	...	F	F.c.	...	...	...	...	O	...	R	R	...	260	.....
27.24	Olive-gray, calcareous weathered ash	A	...	F	O.c.	...	...	O	...	R	...	R	...	...	310	.....
27.95	Light-olive-gray, calcareous weathered ash	A	R	F	O.c.	...	...	F	...	O	R	R	...	...	230	Some fresh pumiceous ash
28.18	Olive-gray, friable, calcareous weathered ash and microfossils	A	O	A	.....	...	...	O	...	F	O	O	R	O	50	Much fresh pumiceous ash, N 1.515, black glass, N 1.55
28.59	Light-olive-gray, compact, weathered ash	F	...	O	O.c.	...	O	F	...	O	R	...	...	...	300	Some fresh ash, a few pyrite grains
29.60	Light-olive-gray, compact, clayey ash and slit	F	...	O	.....	...	...	O	...	O	...	...	R	...	275	Some fresh ash, N 1.515
30.05	Olive-gray, rather hard weathered ash	F	...	F	F.c.	...	...	...	R	O	R	...	...	...	325	.....
30.48	Olive-gray, rather hard, clayey ash	F	...	F	F.c.	...	...	F	R	...	R	R	...	...	250	.....
30.83	Olive-gray, rather hard, weathered ash	F	...	F	F.c.	...	...	O	...	O	...	R	R	...	275	.....
31.55	Olive-gray, clayey ash	F	...	F	F.c.	...	...	O	...	O	R	...	...	...	210	.....
31.97	Olive-gray, fine weathered ash	F	...	F	F.c.	...	...	...	...	F	R	R	...	...	340	Specks of pyrite on some ostracods
32.39	Olive-gray, slightly porous, rather hard weathered ash, high in ostracods	F	...	A	F.c.	...	...	...	...	O	O	R	O	...	275	.....
33.60	Olive-gray, unconsolidated sand	O	...	O	.....	...	...	...	O	A	F	O	R	R	25	Much clear ash, almost black from minute inclusions; a few orthoclase and oligoclase particles
34.16	Light-olive-gray, friable, sandy, slightly weathered ash	O	...	....	F.l.	...	...	...	...	F	O	...	R	...	40	.....
34.61	Light-olive-gray, friable sand and slightly weathered ash	O	...	....	.....	...	...	...	...	A	O	R	R	R	25	.....
35.05	Light-olive-gray, unconsolidated sand and weathered ash	R	...	....	F.l.	F	...	...	...	F	O	R	O	R	35	Much fresh pumiceous ash, N 1.505, rare grains of yellow tourmaline

35.25	Very light-olive-gray, unconsolidated fine ashy sand with marl matrix	A	...	....	.....	...	....	....	....	A	O	...	R	...	20	Abundant pumiceous fresh glass, N 1.505
35.60	Yellowish-gray, friable, fine sand and marl	A	...	....	.....	...	....	....	....	A	F	O	R	R	20	Rare brown rutile; much fresh clear glass
36.18	Light-olive-gray, friable sand and slightly weathered ash	R	...	....	.....	...	....	....	O	A	F	R	O	...	75	Much clear pumiceous glass, N 1.510
36.40	Light-olive-gray, silty sand and slightly weathered ash	R	...	....	O.c.	O	...	...	R	F	F	...	R	...	....	Much clear, pumiceous glass, N 1.485
36.83	Yellowish-gray, unconsolidated slightly weathered ash	...	...	....	O.l.	O	...	...	O	F	F	R	...	...	40	Some clear, pumiceous glass, N 1.500
37.21	Light-brownish-gray, readily crumbled, slightly weathered ash	R	...	....	F.l.	O	...	O	...	...	...	...	...	...	45	Some clear glass, N 1.500
37.73	Yellowish-brown, sandy friable ash and hard silty ash	O	O	O	F	...	...	...	...	F	O	...	R	...	65	Rare yellow tourmaline, some clear, pumiceous glass, N 1.505
37.92	Very light - olive - gray, lumpy, friable, slightly weathered ash	R	...	....	F.c.l.	...	...	O	...	O	O	...	...	...	45	.....
38.11	Light-buff, unconsolidated calcareous sand	A	O	A	F.c.l.	F	...	...	R	F	O	...	R	...	15	Much glass, some clear, some black owing to inclusions
38.52	Light - olive - gray, porous, calcareous, slightly weathered ash	A	...	O	O.l.	...	...	...	...	F	O	...	O	R	200	.....
38.63	Light-olive-gray, crumbly, calcareous, slightly weathered ash	A	R	F	O.l.	...	...	...	...	O	R	R	...	...	50	.....
38.83	Light-olive-gray, porous, unconsolidated, calcareous slightly weathered ash	A	R	A	F.c.	F	O	F	...	F	O	...	R	...	120	.....
39.01	Olive-gray, porous, slightly unconsolidated, weathered ash	F	F	F	O.c.	O	...	O	...	O	R	R	...	...	80	Some clear, pumiceous ash, N 1.485
40.32	Light-olive-gray, consolidated, mixture of diatoms and slightly weathered ash	F	...	F	A.c.	F	...	F	...	O	O	...	R	...	120	Many small pyrite crystals
40.33	Light-olive-gray, friable, weathered ash with diatoms	R	...	F	A.c.	F	...	F	...	R	R	...	R	...	120	Rare pumiceous ash, N 1.500
40.53	Light-olive-gray, porous, weathered ash	R	...	....	F.c.	F	O	F	...	O	O	R	...	...	160	Some brown and black plant fragments up to 3 mm
41.31	Olive-gray, rather hard, weathered ash	R	...	F	O.c.	F	...	O	...	O	R	...	...	...	175	Rare, fresh, pumiceous ash, N 1.505
42.11	Light-olive-gray, porous, weathered ash with diatoms	R	...	O	A.c.	F	...	F	...	R	R	R	R	...	80	.....
42.74	Light-olive-gray, porous, rather soft, crumbly, weathered ash with diatoms	O	...	F	A.c.	F	...	...	...	...	...	...	...	...	190	.....

TABLE 2.—*Continued*

Depth (Meters)	Description of sample	Carbonate	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quartz	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in % dry wt. solids (After Zeevaert)	Remarks
42.95	Light-olive-gray, porous, crumbly, sub-diatomaceous, weathered ash	R	...	O	VA.c.	F	F	...	...	O	...	...	...	...	200	.....
43.37	Olive-gray, rather hard weathered ash	R	...	F	F.c.	F	F	...	...	R	R	...	...	...	225	.....
43.79	Olive-gray, hard, weathered ash	R	...	F	F.c.l.	F	F	...	...	R	R	R	...	...	130	Much clear, brown to black, fresh ash, N 1.525–1.535, some clear pumiceous ash N 1.505
44.77	Light-olive-gray, porous, crumbly, diatomaceous weathered ash	A	...	O	A.c.	O	F	F	...	O	O	...	O	...	150	.....
45.19	Olive-gray, porous, crumbly diatomaceous, slightly weathered ash	A	...	A	VA.c.	...	...	F	R	F	F	O	O	...	65	Much fresh, clear, pumiceous ash, N 1.505
46.04	Olive-gray, porous, friable, organic, weathered ash	F	...	F	O.c.l.	O	...	A	R	O	O	R	R	...	125	Much fresh, clear pumiceous ash
46.47	Light-olive, porous, weathered ash	F	...	F	F.c.	F	...	...	...	F	F	R	...	...	200	Some fresh, pumiceous ash and brown glass, N 1.535
47.53	Light-olive-gray, crumbly porous coquina and weathered ash	A	...	VA	V.c.	F	...	...	...	O	O	...	...	...	100	Much clear, brown basaltic glass, N 1.530, some white pumiceous glass, N 1.502
47.72	Light-olive-gray, porous, sandy, slightly weathered ash	F	...	O	.....	...	F	...	...	F	F	R	R	...	45	Some fresh, pumiceous ash, N 1.505
47.91	Light-yellowish-gray, crumbly, slightly weathered calcareous ash	A	...	....	O.c.	O	...	...	...	O	O	R	R	...	40	One grain brown tourmaline
48.42	Light-gray lumps, crumbly to hard, slightly weathered ash	O	...	....	.....	...	...	R	...	O	R	...	...	...	35	.....
48.61	Light-gray, crumbly, sand and slightly weathered ash	R	...	....	.....	...	...	...	O	A	F	R	R	O	35	Rare, fresh, pumiceous ash, N 1.510
48.71	Light-yellowish-gray, crumbly sand and very slightly weathered ash	R	...	....	.....	...	...	...	R	O	O	...	...	O	40	Much fresh, pumiceous ash, N 1.515
49.68	Light-olive-gray, crumbly sand and slightly weathered ash	R	...	....	.....	...	...	...	...	A	F	R	O	...	40	A few green tourmaline
49.89	Light-olive-gray, unconsolidated sand and very	R	...	....	.....	...	...	...	F	A	F	O	R	...	30	Some clear, pumiceous glass

49.68	Light-olive-gray, crumbly sand and slightly weathered ash	R	...	...	.....	...	...	...	...	A	F	R	O	...	40	A few green tourmaline

49.89	Light-olive-gray, unconsolidated sand and very slightly weathered ash	R	...	...	.....	...	...	...	F	A	F	O	R	...	20	Some clear, pumiceous glass; also brown basaltic glass; rare green tourmaline
50.59	Light-yellowish-gray, unconsolidated, fine sandy ash	...	...	...	.....	...	...	O	O	A	F	O	O	...	30	Much clear, pumiceous, N 1.510, and brown basalt glass, N 1.535
50.93	Light-yellowish-gray, unconsolidated fine sand and very slightly weathered ash	...	...	...	.....	...	...	...	O	A	F	R	R	...	50	A few pieces of chlorite; also nephelite; some brown basaltic glass
51.12	Light-yellowish-gray, crumbly, porous, fine sand and very slightly weathered ash	...	...	...	.....	...	...	...	O	F	F	O	R	...	50	Rare nephelite, some clear, brown basaltic glass, N 1.540
51.31	Light-yellowish-gray, unconsolidated sand and very slightly weathered ash	...	...	...	R.l.	R	...	...	O	F	O	O	R	...	40	Rare nephelite in rock fragments
52.86	Light-yellowish-brown, fine sandy, very slightly weathered ash	...	...	...	R.l.	R	...	...	...	F	O	R	O	...	35	Nephelite in rock fragments
53.03	Light-olive-gray, unconsolidated sand and a little slightly weathered ash	...	...	...	R.l.	R	...	O	F	A	F	R	O	...	35	Rare tourmaline and zircon
53.20	Light-olive-gray, unconsolidated sand and a little very slightly weathered ash	...	...	...	.....	...	...	O	O	F	F	...	...	...	25	.....
53.50	Light-olive-gray, unconsolidated sand and a little very slightly weathered ash	...	...	...	O.l.	O	...	...	F	A	F	R	R	O	20	Much white pumiceous grains in sand sizes, N 1.510
54.00	Light-gray, unconsolidated silty sand and slightly weathered ash	...	...	...	.....	...	...	...	O	F	F	R	O	...	40	Much white pumiceous grains in sand sizes
54.23	Light-gray, unconsolidated sandy and slightly weathered ash	...	...	...	O.c.	R	...	...	...	F	F	R	R	...	25	Much white pumiceous grains in sand size, some clear brown basalt glass
54.35	Light-olive-gray, unconsolidated fine sand and very slightly weathered ash	...	...	...	R.l.	...	...	...	O	F	F	...	R	O	25	Some pumiceous glass, N 1.510
54.45	Light-olive-gray, unconsolidated fine sand and very slightly weathered ash	...	...	...	.....	...	...	...	R	F	F	R	R	...	25	Few bits of orthoclase, much white pumiceous ash
54.63	Light-olive-gray, unconsolidated sand and very slightly weathered ash	...	...	...	.....	...	...	...	O	F	F	O	R	...	40	.....
55.20	Light-olive-gray, unconsolidated sand and ash	...	...	...	.....	...	...	...	R	F	F	...	R	O	25	Most ash is fresh, some pumiceous, N 1.495–1.530
55.40	Light-olive-gray, unconsolidated granules, sand and ash	...	...	...	.....	...	...	...	...	F	F	...	R	...	10	Most ash and much sand is unweathered, pumiceous
55.60	Yellowish-gray, crumbly sand and weathered ash	...	...	...	F.c.	F	...	...	...	F	F	...	...	...	25	.....

TABLE 2.—*Continued*

Depth (Meters)	Description of sample	Carbonate	Oolites	Ostracods	Diatoms	Sponge spicules	Brown plant material	Black plant material	Quarts	Andesine	Hornblende	Augite	Hypersthene	Biotite	Water content in % dry wt. solids (After Zeevaert)	Remarks
56.11	Light-olive-gray, unconsolidated sand, granules, and slightly weathered ash	...	...	...	.....	...	...	...	O	F	F	...	O	O	20	Most granules and many sand grains are white and pumiceous, N 1.500
57.45	Light-olive unconsolidated coarse sand and a little slightly weathered ash	...	...	...	.....	...	...	...	...	F	F	...	...	O	15	A little pumiceous material in all sizes, N 1.500
57.56	Pepper-and-salt-gray unconsolidated granules and sand and a little slightly weathered ash	...	...	...	.....	...	...	...	O	A	F	R	R	O	15	Some nephelite; many granules and sand grains are white and pumiceous
57.73	Light-olive-gray, unconsolidated granules, sand and slightly weathered ash	...	...	...	.....	...	...	...	O	A	F	R	R	O	10	Pyrite on some grains; many granules and sand grains are white and pumiceous
58.18	Gray, pepper and salt, unconsolidated sand and slightly weathered ash	...	...	...	.....	...	...	...	O	A	F	R	R	O	15	Many particles are white and pumiceous
59.19	Yellowish-brown, unconsolidated pebbly sand and slightly weathered ash	...	...	...	.....	...	...	...	R	A	F	...	O	...	30	White pumiceous glass about one-half of sample, N 1.500–1.510
59.60	Light-yellowish-brown, unconsolidated sandy silt and weathered ash	...	...	...	.....	...	...	...	...	A	F	...	...	...	40	.....
59.80	Yellowish-gray, crumbly, sand and very slightly weathered ash	...	...	...	F.l.	O	...	...	...	A	F	...	R	...	55	Clear glass common, N 1.490–1.510
60.01	Yellowish-gray, unconsolidated, sandy silt and slightly weathered ash	...	...	...	O.l.	...	...	...	...	F	O	...	R	...	40	.....
60.40	Light-brownish-gray, unconsolidated sand and slightly weathered ash	...	...	...	O.l.	...	...	...	...	F	F	...	R	O	30	.....
61.10	Yellowish-gray, friable silty ash, very slightly weathered	...	...	...	R.l.	...	...	O	...	O	O	...	...	...	5	.....
61.53	Yellowish-gray, friable sand and slightly weathered ash	...	...	...	.....	...	...	...	...	F	F	O	O	O	20	An occasional pyrite crystal
62.85	Light-olive-gray, friable silty, slightly weathered ash	R	...	...	F.l.	O	...	O	...	F	F	...	R	O	40	An occasional pyrite crystal, some oligoclase
69.05	Light-olive-gray, unconsolidated sand and weathered ash	F	...	F	F.c.	F	...	O	...	O	O	...	...	...	130	Some fresh basaltic glass, N 1.535

TABLE 3.—PETROGRAPHIC DESCRIPTION 80 BELLAS ARTES

Depth (meters)	
3.60–3.80	Light-yellowish-brown, crumbly, sandy weathered ash; coarse and medium sand grade sizes consist of rock particles, mineral grains, oolites, and fossils; about half the sand weathered and unweathered rock particles; weathered particles gray to brown, filled with calcite; treatment with acid yields residue of brown weathered ash; unweathered grains either dense rock particles, gray, hypocrystalline and hyalopilitic, round to subangular; or irregular-shaped white pumiceous particles; mineral grains are angular andesine, hornblende, augite, and hypersthene, most quite fresh, many with glass rim, but hacksaw termination, and iron stain on some pyriboles; clear, angular quartz and brown biotite flakes rare; oolites gray to buff, spherical to ellipsoidal; brown macerated plant material and black charcoal common; some white to translucent ostracod tests, some of which are thickened with carbonate and are then light buff, a few bits of white gastropod shells Fine sand, silt and clay sizes are mixture of weathered brownish ash, white pumiceous partles, N 1.503; brown, clear basaltic ash, R.I. 1.535; calcite particles, from 20 microns to dust sizes; circular diatoms and specks of black and brown plant material
4.40–	Yellowish-brown, friable, sandy weathered ash; no unweathered ash or ostracod tests; oolites frequent, sponge spicules common; rock fragments nearly all weathered; some dense, hard grains; otherwise much like 3.60–3.80; an occasional fragment of red pottery
5.10–5.20	Yellowish-brown, porous, friable, sandy weathered ash; grains greater than ¼ mm are of gray oolites, rock particles mostly weathered, ostracod tests, andesine, hornblende, biotite, bits of brown and black plant material, fragments of gastropod tests; finer material is weathered ash, calcite specks, a few clear brown basalt glass particles, mineral grains, lens-shaped diatoms and white opaline material which is either in tubelike or irregular grains often filled with brown clay-like material
5.70–5.90	Yellowish-brown, soft marl; residue after HCl consists of irregular-shaped, porous, rather soft, light- to dark-brown particles with slight aggregate birefringence, N. near 1.500; deeper colored grains may go up to 1.520; before HCl, particles filled with and surrounded by fine calcite up to 10 microns; clear mineral grains of angular andesine, needlelike green hornblende, all in silt size
5.90–6.10	Light-yellowish-brown marl, much like 5.70–5.90, but carrying many white to light buff ostracod tests and a little fresh, colorless, clear isotropic, glassy ash filled with bubbles, N. near 1.500
7.40–7.60	Yellowish-gray, friable, sandy weathered ash; mostly buff rock particles, some ostracod tests, and andesine and hornblende grains; rock particles slightly weathered, hyalopilitic and hypocrystalline with a few microphenocrysts of feldspar and green hornblende
8.60–8.80	Yellowish-gray, rather hard weathered ash; after HCl residue of light- to dark-brown unstained particles; other weathering products a composite of micaceous and dustlike particles too small to determine; about 5% is fresh unweathered pumiceous, glassy and hypohyaline grains with microphenocrysts of andesine, hornblende and hypersthene; N. of glass 1.505 Andesine and hornblende grains often with glass rim, N. 1.505; few buff ostracod tests and bits of black plant material; calcite, 12 microns to dust size, common and acts as cement
9.00–9.20	Olive-gray, rather hard, calcareous weathered ash; calcite up to 12 microns; after HCl residue a brown composite of weathered ash and sapropel, with from almost isotropic to slight aggregate birefringence; some bits of clear, angular feldspar, hornblende and rare circular diatom tests
9.40–9.60	Olive-gray, compacted, calcareous well-weathered ash, abundant calcite particles up to 15 microns; after acid a composite of brown altered ash particles, clay and sapropel; few small fresh grains of andesine, hornblende, fresh clear glass, N. 1.515, brown glass, N. 1.535, some translucent, ostracod tests, many circular diatoms and sponge spicules
9.60–9.80	Light-olive-gray, compact, calcareous weathered ash, few ostracod tests, many circular diatoms, some bits of black plant material, andesine, and hornblende; calcite in fine particles throughout sample; after acid residue same as 9.40–9.60
10.00–10.20	Yellowish-gray, fine-grained, hard, calcareous, clayey, weathered, iron-stained ash; frequent translucent ostracod tests, some circular diatoms, and black plant particles; much andesine, rare green-brown hornblende, and clear quartz; calcite as scattered fine particles, clay and sapropelic material coat weathered ash; a few minute aggregates of pyrite
11.00–11.20	Light-olive-gray, silty, calcareous weathered ash, mottled with small white irregular opaline patches up to 3 mm across; residue after acid a brown weathered ash, clay, sapropel, and occa-

| | | |

TABLE 3.—*Continued*

Depth (meters)	
	sional grains of andesine, hornblende, and minute pyrite crystals; many circular diatom tests and some sponge spicules scattered throughout
12.80–13.00	Olive-gray, dense, clayey weathered ash, with some light-gray patches which are mostly ostracod tests; residue after HCl a mixture of black organic material, weathered ash, diatom tests and sponge spicules; probably a mixture of a microcoquina layer and a weathered ash layer high in diatoms
13.02–13.20	Much like the dark-gray dense phase of sample above except that diatom tests are not abundant
14.10–14.60	Light- to dark-olive-gray friable lumps which are a microcoquina of ostracod tests and circular diatoms; residue after acid, diatom tests, weathered brown ash particles and a little clear fresh pumiceous ash; few separate mineral grains of Ca-oligoclase, andesine and hornblende, many with glass rim
15.80–16.00	Yellowish-gray, fine-grained, rather hard clayey ash with small cavities; some cavities have form of ostracod tests but others irregular in shape and up to 3 mm across; little fine-grained calcite but most rock a brown, weathered, iron-stained clayey ash; black specks of organic material common, some clear isotropic unweathered pumiceous ash, N. 1.505, in which are microphenocrysts, 20–40 microns, of clear feldspar and rare needlelike brown and green hornblende
16.60–16.80	Olive-gray, well-consolidated clayey ash; much like 15.80–16.00 but with considerable fine calcite, many ostracod tests and particles of brown-stained opaline material, N. 1.440 to 1.480
17.60–17.80	Light-olive-gray, rather hard weathered ash; mixture of brown weathered ash particles, fine-grained calcite, fragments of ostracod tests, circular diatoms and occasional andesine, hornblende and augite grains
18.20–18.40	As above but with some buff opaline grains, N. near 1.45
19.80–20.00	Similar to 17.60–17.80 but less carbonate, a few small patches of minute pyrite crystals and a few ostracod tests, and a few small patches of black plant material
20.40–20.60.	Olive-gray, friable, sandy weathered ash; many white, splintery, opaline fragments, N. 1.44, up to 2 mm; many have—surface pattern suggesting formation on plant material; the few oolites variable, some smooth, others with microbotryoidal surface; a few show a geodelike center; white to gray to dark-steel-gray, a few buff to brown; ostracod tests translucent to white, some buff or gray and much thicker than rest, thickening results from the deposition of carbonates; frequent circular diatoms, and fresh andesine grains; quartz, augite and biotite rare; after HCl a residue of weathered particles, with about 5% unweathered glassy ash, N. 1.505–1.515, with minute feldspar and pyribole grains
21.60–21.80	Pale-yellowish-brown, friable, calcareous weathered ash; 95% in silt-clay sizes; mixture of fine carbonate, brown weathered ash, and fresh ash, which consists of clear micropumiceous glass, N. 1.520, with andesine and microlites of pyribole; occasional brown glass, N. 1.535, carrying infrequent laths of labradorite, and hypohyaline grains that are black owing to dustlike inclusions, N. 1.540
21.80–22.00	Pale-yellowish-brown, rather hard clayey ash; sample consists of brownish weathered ash carrying black plant material, frequent circular diatoms, a few ostracod tests, a few small pyrite aggregates and andesine grains
22.40–22.60	Light-olive-gray, almost soil-like, calcareous weathered ash with irregular, tubelike openings up to 1 mm in diameter like root canals; curved, amber-colored, translucent, irregular and hourglass-shaped structures of ¼ and ⅛ mm long; many brown and black specks of plant material; the rest a mixture of brown, weathered, almost isotropic particles, N. 1.505; frequent carbonate dust; rare unweathered, clear, glassy, N. 1.495, ash particles; some feldspar and rare hornblende grains
22.80–23.00	Light-olive-gray, rather hard weathered ash; more than 99% goes through ⅛ mm sieve; weathered ash gives slight aggregate birefringence, N. 1.500; few small black organic particles, microfossils, pieces of clear micropumiceous glass; calcite as dust and minute rhombs common; some clear andesine, green-brown hornblende, and rare augite grains
23.00–23.20	Olive-gray, rather hard weathered ash; 95% below sand size and most of the rest easily broken rock particles; some specks of pyrite, frequent fine calcite and black organic particles
24.00–	Light-olive-gray, rather hard clayey ash; many minute black organic particles, some pyrite specks,

TABLE 3.—*Continued*

Depth (meters)	
24.20	a few amber-colored, translucent, curved structure (beetle-cases?), and calcite in a brown weathered composite; rare bits of brown basaltic glass, some irregular opaline material and a few clear andesine and hornblende grains
25.20–25.40	Light-olive-gray, rather hard, splintery clayey ash; mostly a composite of fine light brown, slightly weathered microcrystalline particles with slight aggregate birefringence, N. generally near 1.500, but varies from 1.480 to 1.525; many specks of black organic material up to 15 microns, a few pieces of black charcoal up to 3 mm; some pyrite crystals, a few amber fragments (beetle-cases?); many circular and lens-shaped diatoms, occasional ostracods, some micropumiceous clear glass, N. 1.515, a few fine sand size andesine and hornblende grains; particles of calcite throughout sample
26.20–26.40	Light-olive-gray, soft, almost fluffy, calcareous, weathered ash; 97% less than 1/16 mm; mixture of microfossils, fine carbonate, and light-brown, slightly weathered hypocrystalline particles, N. 1.490–1.525, but most near N. 1.500; many clear, micropumiceous glass, N. 1.515, occasional light-brown glass, R.I. 1.535, with feldspar laths; feldspar fresh, mostly andesine but some labradorite and orthoclase; some hornblende; clear glass rims common around mineral grains
28.60–28.80	Light-olive-gray, fluffy, calcareous weathered ash much like sample above but many particles of black organic material and up to 15% clear, glassy, and hypocrystalline micropumice, N. 1.520; a little brown glass without bubbles; many andesine, some quartz and augite, rare hypersthene grains
29.20–29.40	Dark-olive-gray, calcareous weathered ash with patches of light gray; evidently a combination of two layers, a dark-gray, fine-grained, hard phase, 90%; and an almost white, porous, ostracod microcoquina, 10%; after HCl residues of both were alike; brown weathered particles, some clear, glassy, and microcrystalline ash and occasional brown glass; feldspar and hornblende clear, many with clear glass rim
30.40–30.60	A rather hard, light-olive-gray weathered ash with irregular friable patches high in ostracod tests; some ostracod tests and many fine calcite specks throughout the rest; residue after acid, weathered ash, large circular diatoms and some fresh andesine and hornblende grains
31.00–31.20	Olive-gray, unconsolidated, calcareous weathered ash, many white ostracod tests and circular diatoms; some very clear, smooth but irregular-shaped quartz, fresh angular andesine and hornblende grains, often with glass rim; after acid a residue of iron-stained ash, many black organic particles and some clear glassy N. 1.515 and dark glassy, inclusion-filled grains
32.12–32.30	An unconsolidated pepper and salt gray, friable ashy sand, mixture of rock particles, mineral grains, and circular diatom tests; rock particles of sand size from dense, fresh, sub-angular, to porous, weathered; the ash a mixture of almost white, pumiceous and clear brown glassy basaltic particles; mineral grains clear, angular feldspar, mostly andesine but some Ca-oligoclase, labradorite and hornblende; rare quartz, olivine, augite, and hypersthene; salt and pepper effect due to light-colored pumice and feldspar mixed with dark basalt glass and pyribole
33.75–33.90	Gray, pepper and salt, friable ashy sand; medium and coarser sand sizes are feldspar, rock particles and hornblende, with little quartz, augite, hypersthene, and brown plant material; all feldspar fresh and angular andesine; pyriboles, fresh, angular, cleavage fragments and prism forms; quartz, clear, mostly angular but rounded grains and double pyramids present; rock grains dense gray hyalopilitic and microcrystalline and almost white hyaline pumice, some partly rounded Fine sand and smaller sizes mostly clear, glassy pumiceous grains, N. 1.470–1.509, with some brown volcanic glass and some glass filled with dustlike black magnetic inclusions; more pyriboles than feldspar; much fine calcite and some fragments of diatom tests
34.10–34.20	Light-olive-gray, friable ashy sand; coarse sand and larger sizes a mixture of rock fragments and mineral grains; larger grains rounded to subrounded rock fragments, mostly dense gray hyalopilitic; few are pinkish to red and some pumiceous; andesine and hornblende commoner in smaller sizes; some quartz, augite and rare hypersthene grains in medium sand fraction; all mineral grains angular, fresh, except some well rounded quartz; medium sand and smaller fractions a mixture of mineral grains, weathered rock and ash; ash either clear glassy pumice, brown basalt, or glass filled with black inclusions; no clay material, much carbonate dust
35.22–35.40	Yellowish-gray, friable clayey ash; some gray to buff, spherical to ellipsoidal oolites; about 80% brown weathered irregularly shaped hypocrystalline and hyalopilitic ash grains with black or-

TABLE 3.—*Continued*

Depth (meters)	
	ganic material up to 15 microns, some clear, glassy and hypocrystalline ash; the rest mineral grains, many andesine, rare orthoclase, hornblende, hypersthene, augite and biotite; calcite in small grains and dust about 1%
36.36–36.50	Unconsolidated, medium-gray, sandy calcareous ash; with colites, microfossils (ostracod, diatom tests, sponge spicules) weathered rock particles, fresh ash and mineral grains; oolites white to steel gray, spherical to ellipsoidal; most of ostracod tests small and white, some thickened with buff carbonate material; some andesine, hornblende, rare orthoclase, augite and hypersthene mineral grains all fresh and angular; nearly equal parts clear pumiceous ash, N. 1.49, and brown weathered ash make up about half the sample
37.36–37.82	Mixture of pepper and salt, light-gray sandy ash and dark-gray sandy ash lumps; light-gray lumps carry many white ostracods and a few brown basalt glass grains in matrix of slightly weathered and fresh pumiceous ash, N. 1.505; dark lumps mostly brown basalt grains that vary from hyaline, N. 1.550, with few feldspar laths to hyalopilitic filled with felty labradorite laths; some circular and lens-shaped diatoms, calcite particles; few grains of andesine, hornblende, augite and hypersthene
38.21–38.40 and 39.10–39.20	Light-olive-gray, fairly hard weathered ash; some separate mineral grains, few oolites, many microfossils and bits of black plant material up to 1 mm; ash soft brown weathered, irregularly shaped, particles and few unweathered clear pumiceous glass; fresh andesine, and hornblende
40.90–41.10	Light-yellowish-gray, unconsolidated sandy ash; many white ostracod tests, mostly broken; circular diatoms, sponge spicules, some bits of black carbonized and brown macerated plant material in matrix of brown weathered ash; few andesine and hornblende grains
41.90–42.16	Light-olive-gray, well-consolidated, weathered ash with minute black organic particles and microfossils (ostracods, diatoms, sponge spicules); some mineral grains and clear, glassy to hyalocrystalline, ash
42.80–43.01	Yellowish-gray, friable, calcareous sandy ash; variable sample, mostly ostracod tests and oolites in a matrix of brown weathered ash; brown weathered material with some oolites and ostracod tests; oolites have buff warty surface and roughly ellipsoidal; in thin section oolites nearly clear calcite centers with no observable nuclei and buff, fine-grained warty borders; many ostracod tests thickened with similar buff, warty carbonate; residue after acid mostly brown weathered ash some fresh pumiceous ash, N. 1.505, few andesine and pyribole grains sometimes with a glass rim
43.40–43.60	Light-olive-gray, silty, calcareous weathered ash; many white ostracod and circular diatom tests, bits of black and brown plant material, some small clusters of minute pyrite crystals in a matrix of brown weathered ash and fine calcite particles, some clear andesine and hornblende, the latter usually fresh but sometimes with hacksaw termination
43.98–44.17	Light-olive-gray, porous weathered ash, with many fine calcite grains, circular diatom tests, sponge spicules, large gray ostracod tests, fragments of pelecypod shell up to 3.0 mm. and amber-colored fragments, N. 1.595; few fresh angular feldspar and pyriboles grains
45.12–45.31	Light-olive-gray, fine-grained weathered ash in which are white ostracod tests, circular diatoms, sponge spicules, and bits of black plant material; some grains fine calcite, clear brown basaltic glass, andesine and pyribole
46.80–47.00	Yellowish-gray, salt and pepper, friable sandy ash; mixture of dense, sub-rounded microcrystalline and hyalopilitic rock particles, fresh, angular andesine, hornblende, augite and hypersthene, and some clear brown basaltic glass; rock particles decrease and the basalt glass and mineral grains increase in finer grade sizes; some white pumiceous ash, N. 1.505, in silt and fine sand
47.20–47.40	Light-olive-gray, friable sandy ash; fine sand and coarser mixture of sub-angular to sub-rounded, gray to brownish-red, dense, hyalopilitic to microcrystalline rock particles; fresh and angular andesine, hornblende, augite, and hypersthene grains; pyriboles often with prism faces and sometimes clear glass rims, N. 1.505; very fine sand and silt sizes contain slightly weathered microcrystalline ash, mineral grains of andesine and pyribole, a little opaline material and few fragments of circular diatom tests
48.40–	Light-olive-gray, friable, slightly weathered sandy ash; similar to 47.20–47.40, a mixture of sub-

TABLE 3.—*Continued*

Depth (meters)	
48.65	rounded rock particles and mineral grains; in very fine sand and silt some light brown to black basalt grains, a few bits of brown biotite, black organic material, white opaline material and sponge spicules
49.94–50.40	Light-olive-gray, friable sandy ash; similar to 47.20–47.40, but finer grained; no microfossils; clear pumiceous glass, N. 1.505, brown glass, N. 1.505
51.00–51.20	Yellowish-gray unconsolidated sand; coarse sand size mostly gray, but some green and black, dense sub-angular hyalopilitic rock particles, grains of andesine and labradorite, some smooth but irregular-shaped, clear quartz, a few with pyramid terminations; rare pyriboles; mineral grains more frequent in finer sizes; medium sand and finer; about ½ angular rock particles; the rest clear angular feldspar and pyriboles with a little quartz and biotite; a few pyriboles show hacksaw termination; most of rock particles fresh, some show slight weathering
52.27–53.37	Olive-gray unconsolidated ashy sand, evidently a mixture from the meter of depth indicated; as in 51.00–51.20, about 30% each, of rock fragments, of feldspar, and of pyribole grains and ash; rock fragments mostly sub-angular, feldspar clear, angular grains often with glass rims, mostly andesine, a few labradorite, oligoclase, and rare orthoclase; many hornblende, few fresh augite and hypersthene, sometimes with prism forms; some angular, clear quartz; rare green-brown biotite flakes; fresh angular pumiceous ash, N. 1.505, brown angular basalt glass, N. 1.525–1.530 and slightly weathered microcrystalline ash and dark specks of organic material
53.37–53.55	Light-olive-gray, consolidated sandy ash; similar to 52.27–53.37, but has white pumiceous fragments, N. 1.505, in coarser grades
53.54–53.72	Light-olive-gray, unconsolidated sandy ash; similar to 52.27–53.37, but has abundant white pumiceous particles in all grade sizes; pumice is fresh glass, N. 1.505, with very small crystals of oligoclase, andesine, and clear green-brown hornblende; rest a slightly weathered pumiceous, hyaline, and microcrystalline ash
56.80–57.00	Yellowish-gray unconsolidated ash; with rock fragments, mineral grains, microfossils and plant material; the medium and larger sand size grains dense, sub-round to sub-angular, gray to pink, hyalopilitic and microcrystalline rock fragments; many fresh angular feldspar and clear angular quartz; some pyriboles, hornblende, augite and hypersthene, all fresh and usually showing prism faces; fine sand and smaller, mostly slightly weathered, brownish hyalopilitic and hyaline rock particles; some fresh pumiceous ash, N. 1.505, and brown basaltic ash mixed with weathered ash; many brown rootlike and macerated plant fragments
58.80–59.05	Olive-gray, friable sandy slightly weathered ash; angular to sub-angular, gray, dense rock fragments with bits of light brown plant material; few feldspar and pyribole grains in medium and coarser sand grades; fine sand and smaller sizes, mixture of fresh pumiceous ash, N. 1.502, and slightly weathered ash; remainder clear feldspar, hornblende, rare augite, and hypersthene grains and circular diatom tests
59.90–60.05	Olive-gray, unconsolidated ashy sand; fine sand and coarser sizes mostly sub-round to sub-angular hyaline to hyalopilitic dense rock particles, gray, pink, red; a few are porous and brown from weathering; many grains of feldspar, hornblende and quartz; very fine sand and silt fraction as above but about ½ is mineral grains; feldspar, hornblende, augite, quartz, hypersthene and biotite
60.00–60.08	Olive-gray, unconsolidated ashy sand, similar to 59.90–60.05; many quartz grains, few of brown basaltic glass, N. 1.540
61.80–62.00	Olive-gray, unconsolidated sandy ash; medium sand and coarser fraction a mixture of dense to porous weathered rock particles angular andesine and black to red inclusion filled glass; fine sand and smaller fraction irregular-shaped porous brown weathered grains, red iron-stained weathered glass; black magnetic glass; black and brown plant material, and mineral grains; feldspar and hornblende are generally cloudy and iron-stained, quartz angular clear; few brown hairlike particles, ostracods, diatoms, a rare worm tooth; brownish-red iron oxide dust common
63.40–63.60	Light-olive-gray, rather hard, fine-grained slightly weathered almost isotropic ash, (over 99% silt and clay); few feldspar, hornblende and deep-brown biotite fragments; many calcite specks, some circular diatoms, sponge spicules and black bits of organic material
63.60–	Light-gray, well-consolidated fine ash, somewhat weathered, over 99% silt and clay; weathered

TABLE 3.—*Continued*

Depth (meters)	
63.80	ash particles, fresh pumiceous ash, N. 1.502, with many bits of brown and black plant material, clear scattered calcite dust, some andesine, hornblende, clear opaline fragments, lens-shaped diatoms, and rare fragments of ostracod tests
64.00–64.20	Light-gray, porous, friable ash, mostly silty unweathered pumiceous hyaline ash, N. 1.505, in which are microphenocrysts of oligoclase, andesine and green to brown hornblende; in sand fraction are andesine grains, often with glass rim, clear angular quartz and brown flakes of biotite; some glassy ash with black dustlike magnetic inclusions, brown weathered ash, rare bits of black organic material; many whole and broken tests of diatoms and dustlike calcite
65.26–65.40	Light-olive-gray, rather hard fine ash; mostly partly weathered light brown ash with some clear hyaline and dark inclusion-filled unweathered glass; some sand-size grains of clear, angular andesine, and rare hornblende, augite and biotite; many sponge spicules, few fragments of circular diatom tests, scattered patches of fine pyrite crystals
65.85–66.00	Light-olive-gray, unconsolidated fine ash; mixture of slightly weathered brownish irregular-shaped ash particles, N. near 1.520, clear hyaline micropumiceous ash, N. 1.505, and some inclusion filled hyaline ash; some fresh andesine and hornblende, rare quartz, augite, hypersthene and biotite grains; feldspars and pyriboles often with a glass rim, N. 1.505; some circular diatom few ostracod tests; some pyrite partly in tubelike shapes up to ½ mm. in diameter as though formed around rootlets; dark specks of organic matter, a few opaline particles, some egg-shaped, about 7 microns in length
67.68–67.80	A gray easily friable, fine ash, of mixed light-gray and dark-gray slightly weathered ash; light-gray grains microporphyritic hypocrystalline, the glass N. near 1.520, the crystals mostly lath-shaped feldspar, a few hornblende and some needle-like apatite; the dark grains are similar except glass is brown, N. 1.535; many circular diatom tests and sponge spicules
67.80–68.00	Olive-gray, compact weathered cryptocrystalline ash; some fresh andesine and hornblende grains, a few rounded bits of chalcedony
68.40–68.60	Light-olive-gray, friable mixture of slightly weathered and fresh ash; mostly pumiceous, hyaline, microphyric, with feldspar and hornblende phenocrysts; some fresh andesine, hornblende, biotite often with glass rim, N. 1.510–1.520; some circular diatoms, sponge spicules, and fine calcite particles
68.90–69.10	Gray, compact, slightly weathered ash; almost identical with 68.40–68.60 above
69.10–69.30	Light-gray, compact, rather hard, cryptocrystalline weathered ash; some diatoms, sponge spicules, a few of which are enclosed in clear opaline material
69.30–69.50	Light-olive-gray, compact, fairly hard, weathered, sandy ash; mostly iron-stained hypocrystalline and hyalopilitic ash particles, a little pumiceous glass, N. 1.520; many grains of fresh angular oligoclase, andesine and clear green-brown hornblende; few brown ragged flakes of biotite and light brown hypersthene; considerable fine calcite, up to 12 microns; after treating with acid sample crumbles readily; some circular diatoms and sponge spicules
69.50–69.70	Olive-gray, rather hard, slightly weathered, crypotocrystalline, fine ash; little clear pumiceous glass, N. 1.515, many sponge spicules, few bits of ostracod tests and some specks of brown plant material; few quartz, many andesine and Ca-oligoclase, some hornblende, all fresh and angular; few ragged deep brown weathered biotite flakes
69.70–69.90	Light-olive-gray, compact fine ash; as in 69.50–69.70 but with considerable dustlike calcite throughout sample
69.90–70.01	Light-olive-gray, slightly weathered hypohyaline and hyalopilitic ash; few bits of clear orthoclase, quartz, some fresh andesine and hornblende; orthoclase is sometimes in clear pumiceous glass, N. 1.515; few circular diatoms, sponge spicules and black bits of plant material
70.10–70.30	Light-olive-gray, friable slightly weathered ash, as in 69.90–70.10, except feldspar is slightly cloudy and many microfossils
70.30–70.50	Brownish-gray, fine-grained, somewhat friable weathered ash; ash a deep-brown from iron-stain but mineral grains, oligoclase, andesine and hornblende quite fresh and clear; many circular diatoms and sponge spicules
70.50–	Light-olive-gray, friable silty ash, but contains two somewhat irregular fragments, about 4 cms.

TABLE 3.—*Continued*

Depth (meters)	
70.70	across, of dark, sandy friable ash; light-gray phase very slightly weathered, lightly iron-stained hypohyaline ash, with fine sand and silt-size grains of clear, fresh, angular oligoclase, andesine and hornblende; many scattered circular diatoms and sponge spicules; dark sandy phase mostly medium and fine sand contains feldspar and pyribole grains in matrix of clear pumiceous and dark glassy unweathered ash with many minute opaque inclusions; some diatom tests and sponge spicules
70.90–71.10	Light-olive-gray, friable ashy sand mostly medium and fine sand size mineral grains and rock particles; larger grains sub-rounded but fine sand or smaller angular; rock particles range from compact, sub-round to sub-angular, unweathered, to gray and brown porous, irregular-shaped, weathered; quartz, andesine and pyribole grains generally fresh angular; fine sand and finer particles partly fresh, glassy, and partly slightly weathered and iron-stained; many circular diatoms, sponge spicules and fine calcite particles
71.20–71.30	Dark-yellowish-brown, well-weathered ash; less than 1% coarser than 1/8 mm is feldspar and hornblende, some fresh most slightly weathered; rest deeply iron-stained, weathered ash, a few mineral grains, some scattered bits of black and brown plant material, circular diatoms, sponge spicules, and calcite dust
71.30–71.50	Light-olive-gray unconsolidated sand; coarse sand size brown to gray, sub-round to sub-angular rock particles, few feldspar, quartz and hornblende grains; in medium and fine sand fraction about 3/4 of particles angular slightly clouded and rusty Ca-oligoclase and andesine, clear angular quartz, hornblende, some augite, hypersthene, and biotite flakes; many white uncoated and brown carbonate coated ostracod tests; the latter grade into brown, warty, oolitic-looking grains; remainder gray and brown iron-stained, angular rock particles; fine sand predominantly mineral grains, mostly Ca-oligoclase and andesine, some hornblende, augite and hypersthene, all glassy, many showing prism faces; silt and finer sizes a composite of irregular, somewhat weathered rock particles, mineral grains (feldspar and pyriboles) bits of ostracod test, circular diatom tests and calcite dust
71.90–72.40	Several small lumps of well-compacted but friable silt-sized ash; most of the lumps very light-olive-gray, the rest dark-gray color; the light-olive-gray phase is mixture of very slightly weathered to unweathered ash, many circular diatom tests, sponge spicules and a few pieces of green-brown hornblende; dark-gray phase is similar to lighter phase but ash iron-stained and weathered
72.55–72.70	Dark-yellowish-brown, friable sandy ash; sand grains mixture of rock particles, oolites, ostracod tests and mineral grains of andesine, hornblende and hypersthene; rock particles vary from brown weathered, to gray, pink and red unweathered; coarse sand somewhat rounded but the rest quite angular; oolites brown mostly smooth, occasionally warty; most ostracods tests thickened with calcite and some valves completely filled; some angular mineral grains, andesine and hornblende, usually fresh sometimes iron-stained; silt and finer particles weathered ash, clear pumiceous ash, bits of microfossils, mineral grains, and fine dustlike calcite
72.70–72.80	Yellowish-gray compact ash with a few white patches up to 0.5 cm; gray material is weathered ash, diatoms, sponge spicules, and mineral grains; white patches almost entirely fresh ash, mostly glass but some are hypocrystalline
72.80–72.90	Light-olive-gray, friable, glassy and cryptocrystalline almost fresh ash, N. 1.510; some diatoms, sponge spicules, grains of fresh angular andesine, hornblende, quartz
72.85–73.01	Light-olive-gray, compact, rather hard, weathered cryptocrystalline ash; mostly iron-stained irregular particles, some circular diatoms, sponge spicules, andesine, hornblende and black specks of plant material
73.15–73.30	Light-olive-gray, compact slightly weathered sandy ash; ash mostly irregular-shaped silt and smaller particles with cryptocrystalline texture; sand sizes a mixture of dense rock particles, mineral grains and weathered ash; mineral grains fresh, angular andesine, some fresh hornblende and augite but some with hacksaw terminations
73.45–73.60	Yellowish-gray, slightly weathered silty ash, sand grains hyalopilitic and cryptocrystalline rock particles, somewhat rounded; mineral grains fresh angular andesine, hornblende, and quartz; silt and finer fraction glass and hypocrystalline ash particles; some circular diatom tests; a few sponge spicules

TABLE 3.—*Continued*

Depth (meters)	
73.75–73.90	Medium-gray, rather hard, somewhat weathered, silty ash, with purplish brown streaks; particles are cryptocrystalline to hypocrystalline iron-stained ash with many clear andesine and some hornblende grains; purplish streaks due to manganese
74.05–74.20	Light-yellowish-gray, well-consolidated but slightly porous, somewhat weathered hypocrystalline and hyalopilitic ash; few grains of andesine, little fine calcite; some circular diatoms, few sponge spicules
74.85–74.90	Light-olive-gray friable sandy ash; sand size rock particles rounded, dense to porous, all slightly weathered; separate andesine, hornblende, augite and hypersthene mineral grains, all fresh, often with glass rim; silt and finer fraction cryptocrystalline ash light brown from iron-stain

TABLE 4.—PERCENTILE DISTRIBUTION IN GRADE SIZES (IN MM) OF SAND AND ASH FROM 80—BELLAS ARTES CORE

Depth (meters)	4–2	2–1	1–½	½–¼	¼–⅛	⅛–1/16	<1/16
3.60–3.80	..	..	4.3	10.4	13.5	10.6	60.8
4.40–4.60	..	..	6.1	5.5	6.5	9.1	72.8
5.10–5.20	..	..	4.5	2.7	3.8	7.0	82.0
7.40–7.60	..	6.1	10.1	8.1	6.0	12.8	55.6
20.40–20.80	..	..	0.1	2.5	4.1	8.3	85.0
32.12–33.30	..	..	1.4	13.3	32.2	35.0	20.1
33.75–33.90	..	1.5	7.5	6.7	11.9	20.4	51.0
34.10–34.20	1.0	3.2	11.4	20.2	36.1	15.0	13.1
40.90–41.10	..	..	0.9	4.4	7.4	56.2	31.1
42.80–43.01	..	2.6	15.5	49.0	14.9	30.	14.8
44.17–44.36	..	..	2.4	5.2	20.4	44.8	27.2
46.80–47.00	..	..	..	5.4	10.7	14.8	69.1
47.20–47.40	..	..	..	6.0	17.4	14.4	62.2
48.40–48.65	..	..	..	4.8	13.0	18.1	63.9
49.92–50.40	..	0.6	1.2	2.6	5.4	5.9	82.1
51.00–51.20	5.4	11.3	25.8	32.7	15.8	5.4	3.5
52.27–53.37	..	0.6	1.5	8.6	24.4	29.7	35.3
52.37–52.55	2.3	3.5	6.4	21.2	36.2	26.1	4.4
53.54–53.72	..	..	1.0	16.2	31.9	29.6	21.2
56.80–57.00	2.4	2.6	5.9	11.1	11.2	9.9	56.9
58.80–59.05	..	0.5	9.6	20.0	23.7	26.2	19.9
59.90–60.05	9.1	12.1	12.7	21.5	15.4	9.8	15.3
60.80–61.00	..	1.3	4.5	12.6	25.0	33.6	24.0
61.80–62.00	..	..	9.2	11.7	20.0	30.6	28.6
64.00–64.20	..	..	..	..	3.7	28.6	67.8
65.85–66.00	..	..	..	..	0.5	0.7	98.8
70.90–71.10	..	2.1	3.9	2.7	24.5	39.9	26.8
71.30–71.50	3.2	5.5	6.5	32.8	36.3	13.5	1.9
73.45–73.60	..	..	1.2	1.7	2.0	1.9	93.2
74.75–74.90	1.5	4.9	4.6	6.1	13.3	19.6	49.9

that the only change was a decrease in value from two to four digits.

On some samples that obviously contained clay differential thermal analyses were run. This work was done at Columbia University in the laboratory of Professor Paul F. Kerr and followed standard procedures.

TERMINOLOGY AND CLASSIFICATION

In describing the core samples the terminology and classification suggested by Wentworth and Williams (1932) for the pyroclastic rocks are used. However, the origin of many samples may not be that described for a pyroclastic by these authors. Hay (1952, p. 119) has discussed a similar problem in relation to his study of the Absaroka Range volcanics, and he has used the adjective "detrital volcanic" in the place of "pyroclastic" where most or all of the rock is of fragments derived from the erosion of contemporaneous or older volcanic rocks. In spite of the difficulty in recognizing origin, it is probable that most of the allogenic particles in the samples studied came either from material ejected from volcanoes or eroded from the vesicular phases of flows. The surface rocks of the Mexico City basin and surrounding hills are all products of volcanic activity—flows, ash, tuff, volcanic detritals—or weathered and partially weathered products of these rocks. All these rocks belong to a single petrological province. The close kinship of ejecta and flows, that are often microvesicular like those of Parícutin, restricts exact usage of the classification terminology. However, many of the fragments of these samples are doubtlessly pyroclastic, for Segerstrom (1950, p. 38) notes that the volume of ash from Parícutin is two or three times that of the associated lavas, and this may be a fair indication of the proportion of ash to lava in the Mexico City area. Most of these sediments, if indurated, would be called tuffs by the petrographer. In some samples, however, the shape

TABLE 5.—SUMMARY OF 80—BELLAS ARTES AND 57—MADERO SEDIMENTS

Dominant type	Diagnostic characteristics	Inferred lake conditions	Inferred volcanic and tectonic activity
Zone II: Bellas Artes 3–8 m—Madero 3–8 m			
Weathered ash and some sand; some fresh pumiceous ash and brown glass in most samples	Water content moderate; CO_2 medium to high; SO_4 and Cl below 0.05% by weight; oolites common; plant root holes common	Variable but generally low water; slightly saline	Slight and intermittent volcanism
Zone III: Bellas Artes 8–32 m—Madero 8–34 m			
Weathered clayey ash with small amounts of fresh ash	Water content usually high, but low in fresh ash and micro-coquina layers; CO_2 moderate to high; SO_4 and Cl trace; ostracods and diatoms common; sapropel and pyrite common; plant root holes occasional	Alternating open water and swampy conditions, lake relatively shallow	Some volcanism but not close to this area; relatively stable time
Zone IV: Bellas Artes 32–37 m—Madero 34–37 m			
Ashy sand only slightly weathered; a few well-weathered horizons	Water content very low; CO_2 content variable; no SO_4 or Cl; diatoms and sponge spicules common; sand and ash show little sorting	Rapid deposition of sediments; bar or beach (?); low salinity	Intermittent tectonic activity with intervening quiet periods
Zone V: Bellas Artes 37–45.3 m—Madero 37–47.5 m			
Weathered clayey ash, some sandy beds in middle part, and thin fresh acidic and also basalt ash in lower part	Water content high; CO_2 high in lower part; no SO_4 or Cl; oolites only in upper half; plant root holes near bottom; many ostracod and diatoms	Water always shallow; swampy at times	Only slight volcanic effects in this area; a relatively stable stage
Zone VI: Bellas Artes 46–61 m—Madero 47.7–61 m			
Ashy sand and sandy ash; little weathering; poorly sorted	Water content very low; no CO_2, SO_4, Cl, or oolites; few fossils; plant root holes in upper part	Rapid deposition of sediments; bar or beach deposits(?); salinity very low	Active tectonic stage
Zone VII: Bellas Artes 61–75 m			
Alternating fresh and weathered ash; some sandy layers	Water content high only in weathered ash; slight CO_2 at 72.55 m only; slight SO_4; no Cl; plant root holes in some layers	Depth variable but swampy at times; very slightly saline; fresh ash deposited rapidly; weathered ash deposited slowly	Strong but intermittent volcanism with some sporadic tectonic activity

size, and texture of the particles indicate derivation from the erosion of lava flows; in others, the authigenic nature of the particles, when organic or chemical in origin, is obvious. In still others the origin is masked by the formation of hydrolyzates. Many samples exhibit particles which have more than one, and sometimes all, of these sources. In most cases, however, the greater part of these cores is composed of pyroclastics, and the classification of Wentworth and Williams can be used with appropriate qualifying adjectives.

This classification makes no allowance for pyroclastics that are mixed with other detritals. Ash is defined as being of sand size, 4 mm and less, and "without qualifying adjective, ash should be applied to essential or juvenile ejecta" (Wentworth and Williams, 1932, p. 45). Krumbein and Sloss (1951, p. 134) and Pettijohn (1949, p. 265) have introduced terminology to denote mixtures of ash and nonejecta particles when the rock is indurated; they suggested "tuffaceous sandstone" and even "tuffaceous sand" but offered no terms to describe mixed unconsolidated materials. The term "ash" will be used as defined by Wentworth and Williams; for allogenic material, not of pyroclastic origin, description will be based on texture and will follow the Wentworth (1922, p. 381) classification. Thus where ash is predominant but the allogenic particles of sand or silt exceed 10 per cent the term "sandy ash," or "silty ash," is used. Where clay is 5 per cent or more "clayey ash" is used. If allogenic particles are dominant and eroded particles are between 50 and 90 per cent by weight of the sample, and if ash is more than 10 per cent, then "ashy sand," "ashy silt," or "ashy clay" is used.

Physiography and Climate

The Cuenca of Mexico is in the southern part of the Central Plateau of Mexico (Ordonez, 1936, p. 1291) which stretches from the New Mexico-Arizona border to about 50 miles south of Mexico City. On the west boundary of this plateau is the Western Sierra Madre, on the east the Eastern Sierra Madre, and on the south the Balsas Basin. The southern part of this province, the South-Central Plateau of Ordonez, is characterized by high-altitude valleys, humid climate, interior drainage, and enormous amounts of volcanic extrusives that differentiate it from the wide bolsons of the North-Central Plateau.

The Mexico City basin extends north-south for nearly 70 miles and is about 15 miles wide. The lake floor and its drainage area cover about 3000 square miles (7580 sq. km). The basin is much narrower where the hills of the Serrania de Guadalupe, formed from a series of andesite and related flows and tuffs, extend from the west side of the valley just north of the city, and where the Serrania of Santa Catarina, a group of small, recently extinct volcanoes, project from the eastern side 10 miles south of the city.

At present the basin contains seven shallow remnants of lakes; from north to south they are: Zumpango (7358 ft.), Xaltocan (7347 ft.), San Cristobal (7347 ft.), Texcoco (7336 ft.), Mexico (7339 ft.), Xochimilco (7337 ft.), and Chalco (7337 ft.) These elevations are taken from a map by Arellano (1951). During the Pleistocene a lake covered the entire floor of the basin, an area of 630 square miles. Although many small streams flow into it today, none is permanent, and since the basin has no outlet the water is saline. Only about 10 per cent of the basin floor is covered today by the seven lakes, but even as recently as 1520 A.D., when the Spaniards first entered the valley, almost all of it was covered by shallow water (De Terra, 1949, p. 18).

About 75 per cent of the precipitation in the basin of Mexico City occurs during the summer months, from June to September. Most of this precipitation, caused by convection currents, occurs as heavy afternoon thunder storms and often accompanied by hail. The yearly average for the area is about 700 mm (27.6 in.), and only 588 mm for the valley floor.

The mean temperature of Mexico City is 15.6°C. (60.1 F.). The warmest month is May, mean temperature 18.4°C. (65 F.), and the coolest month is January, mean temperature 12.3°C. (54.1 F.) (Page, 1930, p. 6). As might be expected in a high altitude valley in a region of high relief, the winds are greatly affected by local topography both in strength and direction, and although the prevailing winds are

westerly during the dry winter season and easterly during the warm wet season, the local winds are usually much in variance with these directions.

General Geology

The rocks of the Valley of Mexico are all volcanics and associated ejecta. Little detailed geological work has been done on this complex of flows, tuffs, and ash beds, but the region is in the andesite belt of the North American Cordillera, and most of the rocks are andesites and related types. A published list (1914) of igneous rock types from the Districto Federal shows that 36 of the 49 rocks mentioned were andesites; the remaining 13 were basalts. Eight of these basalts were from the San Pedregal de San Angel flow, which post-dates the arrival of man in the valley. These rocks were names from thin sections alone; only the rock textures were described, and the main mafic minerals—amphibole, augite, hypersthene, biotite, and olivine—listed. Washington (1917) gives seven satisfactory chemical analyses of rocks from the basin and all are andesites but one, and that is a basalt from the Pedregal. Five inferior analyses are also listed and all these are andesites.

That these analyses cover all the lava types is improbable. The author found dacite and trachyte on the Guadalupe Hills, and some of the pumice of the cores suggests rhyolite, but it is obvious that the commonest extrusive is andesite.

Zeevaert (1952) has outlined tentatively the tectonic and volcanic history of the area and a short resumé of his interpretation follows.

No sediments or other rocks older than the Cenozoic intrusives are found in the basin, and no accidental sedimentary, metamorphic, or igneous rock fragments are found among the pyroclastic debris. The nearest known sediments, about 30 miles northeast of the basin are Cretaceous limestones that are thought to have once covered the present Mexico City basin area. These limestones were folded and broken by the Laramide orogeny. The intense volcanic activity associated with the orogeny continued intermittently throughout the Cenozoic; it was especially strong during the Miocene and Pliocene epochs. Throughout Cenozoic time the valley was drained by a river; at the beginning of the Pleistocene, orogenic movements blocked the drainage and formed the present basin where lacustrine sedimentation began.

The conditions of erosion and transportation to which most of the clastics were subjected can be better understood on reading the studies on erosion at Parícutin by Segerstrom (1950). This volcano, which is in the same physiographic, climatic, and petrographic province as the basin of Mexico City, has likely duplicated in its flows and ejecta and in the transportation by wind and erosion by stream of ejecta the events which have occurred many times around the basin of Mexico City.

On freshly fallen ash a rapid crusting occurs, evidently owing to puddling of the surface by rain drops. During this process the fine particles of the freshly deposited ash percolate downward a few millimeters to form a crust which is compact and only slightly permeable, and the coarser particles on top of this crust are carried away by sheet flow. No crusting occurs when ash has been eroded and redeposited by water or by wind. Ash reworked, whether by the water or the wind, has undergone a selective transportation. This eliminates the conditions that gave rise to the crusting.

The Parícutin region, as Mexico City, has torrential summer-time thunder storms, an active agent of erosion from the initial raindrop impact to the final flood-filled arroyo with its tremendous load of ash and other debris. The complete or partial destruction of vegetation by the ash aids this rapid erosion, as does the increased precipitation from the juvenile water from the eruption itself.

Each eruption of the volcanoes surrounding the large Mexico City basin would bring large amounts of wind- and water-carried pyroclastics into the immediate vicinity. Windborne ash would form a continuous layer on the lake floor and would slowly thin as distance from the source increased. The water-carried load of ash would be very thick locally (Dorf, 1951, p. 319), especially near the mouths of the streams that drained the area, but would thin out rapidly. Only the finer particles would reach the central part of the lake when the

depth of the water was greater than the zone of wave action. During periods when the surface area of the lake was restricted and the streams were building fans out into the basin floor, or when the lake was shallow and the effect of wave action could be felt over a great part of the lake floor, even the coarser particles might be carried to the middle of the basin. (*See* percentile distribution, Table 4.)

In this physiographic province wind is an important transporting and eroding agent. De Terra (1949, p. 19) notes that dust storms around Mexico City last for days; in the Parícutin area during the winter visibility is often restricted to less than 100 m by the windborne ash (Segerstrom, 1950, p. 119). The writer collected a specimen of sand from a hollow in the almost treeless Guadalupe Hills just north of Mexico City and about 150 m above the lake plain. This specimen had a carbonate crust 2–5 mm thick, under which the sand was composed of ash and eroded rock particles, mineral grains, ostracod valves, and diatom tests. The ostracod and diatom particles made up almost one-third of the specimen; they could have reached this position only by wind transportation. The ash may have come from either near or distant eruptions, for one 24-hour fall, wind borne from Parícutin, amounted to 136 mg/sq m (Segerstrom, 1950, p. 36).

Allogenic Material

SAND: The term "sand" as used in this paper includes dense, slightly rounded rock particles and separate mineral grains over one-eighth mm; "ash" includes the angular and vesicular glassy and hypohyaline particles larger than one-eighth mm and all other particles less than one-eighth mm in size. This will place many products of erosion in the ash group, but no other distinction seems practical. It is often impossible to determine the origin of the grains except in the coarse sand sizes. The medium sand size and coarser grains are generally slightly rounded and are of a dense, usually hyalopilitic or pilotaxitic texture and can be readily distinguished from ash; the finer sand-sized particles, less than one quarter mm, are often difficult to recognize, and only the characteristic shard shape or veiscular texture of the ash can distinguish the two types, and where the grains have undergone considerable weathering their origin cannot be determined. The sand is prophyritic and carries as phenocrysts the same minerals as does the ash. Some of these phenocrysts are sometimes in the same grade sizes as the ash phenocrysts, but usually they are larger, some up to 2 mm or more in diameter, while those in the ash are seldom greater than one-eighth mm. Where the phenocrysts are separate from the matrix, this difference in size is used as an arbitrary distinction, the only plausible one in this area where all of the rocks are of volcanic origin.

Of the allogenic organic material the most important in stratigraphic interpretation is the plant pollen. Plant fragments, usually macerated and carbonized, are found as well as rare bits of insect chitin. Some of the samples contain a slimy, extremely fine-grained sapropel which, because of its colloidal form, might be termed dy (Twenhofel, 1939, p. 88). The dy is always associated with the more highly weathered samples.

ASH: All the ash is prophyritic. Phenocrysts up to 1 mm occur but these are rare; most of them are one-eighth mm or less in length. These may be feldspar (generally calcic andesine), hornblende, augite, or hypersthene, occasionally quartz and biotite, and rarely olivine, orthoclase, oligoclase, and sanidine. The feldspars are usually prismatic but sometimes tabular, while the pyriboles are invariably euhedral prisms, often showing pyramidal faces. Except in rare cases feldspars and pyriboles are glassy and show few if any signs of weathering.

The matrix of the ash ranges from hyaline to hypocrystalline and is either vitric, vitric-crystal, or crystal-vitric in texture. Much of the ash is vesicular, and ranges from micropumice to fine scoria. Most of the fresh, fine ash found in small amounts in the weathered sediments is either a white, rather acid pumice or a light-brown, clear glass. Intermediate types constitute more of the sample where the ash is coarse.

Authigenic Material

SEDIMENTS OF CHEMICAL AND ORGANIC ORIGIN: Mixed with the clastic material of

the samples are authigenic particles of chemical and biochemical precipitates and organic remains. These form a minor part of the sediment in most samples but in a few they dominate. Authigenic organic remains include ostracod valves, diatom frustules, and sponge spicules; occasional bits of gastropod and pelecypod shells are present in a few horizons.

The most important authigenic minerals are calcium and magnesium carbonates, found in many of the samples, sometimes in large amounts. Calcium carbonate is by far the most common. Apart from organic remains and oolites and a very rare clastic fragment of what seems to be caliche, carbonate is invariably found as very small crystals or aggregates. Under oil immersion these are usually clear, but are sometimes stained a light brown and appear as dust, rhombs, small elongate grains, and fine aggregates. Few individual particles are over 20 microns in length and most are less than 5 microns. A rare grain among the larger rhombs was biaxial, evidently aragonite, perhaps a broken fragment of ostracod test.

Carbonate precipitation in the sediments of a saline lake has been discussed by Eardley (1938) in his study of Great Salt Lake, Utah. The factors governing deposition are both organic and physicochemical and are evidently interrelated. They include evaporation, carbon dioxide concentration, ion concentration of other salts, temperature and atmospheric pressure changes, algae, and bacterial metabolism. Some or all of these factors probably have been active in the precipitation of carbonate in the Mexico City basin, but what part any one of them played is not evident in the samples.

OOLITES: The conditions under which oolites form are not fully known (Krumbein and Sloss, p. 101), but it is well established that they form in saline lakes where the water is shallow and wave activity vigorous (Eardley, 1938, p. 1371), conditions which apply here. The oolites are from one-quarter to 1 mm in diameter; some are spherical, but many are slightly elliptical. Their surfaces are generally smooth but some are warty; the color ranges from a light steel gray to reddish brown, but the warty variety is always reddish brown. On dissolving these oolites in HCl, a residue consisting of a bit of ash, clay, or mineral grain remained. In thin section an occasional grain shows a concentric structure; but most do not show any apparent strcture. The warty reddish-brown variety has formed around either a fragment or an entire ostracod valve, and in some samples there is gradation from ostracod tests which are lightly coated to those in which the carbonate deposition has formed ellipsoidal oolites. Their color is due to iron oxide.

OSTRACODS: The valves of ostracods were found in almost all the samples that carried clay and weathered ash, but were rare in the unweathered ash and sand samples. The significance of these bivalve crustaceans has not been investigated.

DIATOMS: The frustules of these plankton are common in many of the samples and are dominant in a few. Two forms are present: one is disklike and ranges from 30 microns to about 350 microns in diameter, and the other is elongate and tapering, up to 200 microns in length, and is much less common than the disklike type. Welch (1935, p. 186) notes that production of diatoms is governed directly by silica in the water, but the amount of volcanic glass in these sediments is high, which indicates that some limiting factor other than SiO_2 must act to control growth of these plants.

SPONGE SPICULES: Oxeate spicules of the family Spongillinae are common in the samples that contain diatoms but were found in only one sample which had no diatoms. The factors that govern the conditions of growth of both sponges and diatoms would seem to be similar.

WEATHERING

Mineralogy

The evaluation and description of the weathered products of pyroclastics is difficult because the surface area of volcanic ash, especially pumiceous ash, is very great. Volcanic glass is susceptible to rapid weathering as it is metastable, tending to crystallize. There is a low order of orientation in the bonds holding the structure together (Mason, 1952, p. 65), and this lack of symmetry makes the

breakdown of the irregular network of atoms under surface conditions remarkably rapid.

Changes during the initial phase of weathering in the volcanic glass are not known but are probably complex. Hydration probably occurs but its initial effects are not apparent under the microscope. The differential thermal analyses curves of slightly weathered ash all show definite but wide endothermic peaks near 155°C.; water from an initial stage of hydration may account for these low temperature peaks.

The phenocrysts in the ash are generally clear and unweathered even in those samples where the ash is partially changed to clay. Few feldspars show even a slightly cloudy effect, and nearly all the pyroxene and amphiboles are glassy; an occasional one is dull and shows iron stain, and a very rare grain will exhibit hacksaw termination. The biotite, however, is commonly in dull brownish-red ragged flakes. Olivine is rare in the sediments, and where present is in small, rounded, slightly iron-stained grains.

A feature characteristic of many of the mineral grains is a complete or partial rim of glass; this effect is common even in the more highly weathered samples.

Montmorillonite

Aggregate polarization effects are apparent where weathering is more pronounced, but even at a magnification of × 1200 individual grains cannot be resolved. As weathering proceeds a deeper iron stain occurs in the sample, and also the clay mineral, montmorillonite, appears. This clay mineral could sometimes be recognized under the microscope, but its presence, where in considerable amount, was proved by the differential thermal analyses curves. The formation of montmorillonite might be expected in an area where ash and lava flow detritals mainly of andesitic composition have been weathered and hydrated. Conditions of accumulation were favorable to the stability of montmorillonite in this slightly saline lake rather high in carbonate in which water movement through the sediments was slight, a lacustrine environment typical of the "non-aggressive" type as defined by Grim (1953, p. 356).

This clay mineral is found in surprisingly small amounts even in those samples that resemble clay on initial inspection. The samples from the Madero were too small for proper textural analyses, and even the larger samples from the Bellas Artes core were inadequate for satisfactory analyses of the clay-mineral fraction. Most of the weathered ash particles were smaller than sieve size and, on pipette analysis, appeared in the clay-sized group. No satisfactory way of separating clay from weathered ash was found, although one might be if the samples were large enough and had never been allowed to dry. In spite of unsatisfactory results from pipette analyses alone, it was apparent from the fine fraction observed under the microscope that the amount of clay minerals was seldom if ever above 10 per cent of the sample and in most samples, even in those zones that might be called clayey was less than 5 per cent.

Montmorillonite was the main hydrolyzate found in the weathered ash. It was formed on the uplands through weathering and transported with ash and sand into the lake. Little clay was formed after deposition, and fresh-ash layers found throughout the cores have remained unchanged and have no clay.

That solution and precipitation have occurred is shown however by the mineralization of the grains of plant pollen. These grains could not be concentrated or separated from the rest of the sediment until samples were treated with hydrofluoric acid and strong oxidizing agents such as concentrated sulphuric acid, nitric acid, potassium chlorate, and cellusolve.

Soils and Vegetation

Vegetation regrows very rapidly after destruction by ash, and a soil forms. Hardy (1939, p. 61) gives 30 years for a stable forest to be established at the Island of St. Vincent after the vegetation had been destroyed by ash from Soufriere, and Jenny (1941, p. 36) cites the formation of a soil 35 cm thick on the Island of Lang-Eiland 45 years after the Krakatoa explosion of 1883 had covered that island with ash to a depth of over 30 m. Near Jorullo, 300 m from Mexico City, the vegetation was reestablished on the ash after 90 years (Segerstrom, 1950, p. 136).

Definition of Zones

Zone VII

The order of discussion follows that of deposition, that is from zone seven upwards.

The layers of this lowest zone alternate fresh and weathered ash. The weathering is for the most part only slight, but five horizons between 68 and 73 m contain clayey, weathered ash, and in these both the water and pollen content are high. Carbonates are absent except in two horizons, 63.40–64.20 m and 72.55–72.70 m, constituting up to 1.2 per cent only in the lower one. Few ostracods are present and are common at only the 72.55–72.70 m horizon. Diatoms and sponge spicules are present throughout.

This sedimentation suggest intermittent volcanic activity. During quiet intervals the ash was weathered and the forest cover reestablished itself.

Zone VI

Bellas Artes 46–61 m and Madero 47.7–62 m

These samples are mixtures of coarse sand and ash. The textural analyses, Table 4, show a large degree of scatter, but if the silt and clay sizes are disregarded only one maximum is present, in the coarser-size particles. This suggests a single, nonselective agent of transportation and also that after deposition wave work was weak or deposition too rapid for selective sorting. A period of rapid erosion and deposition, the result of tectonic activity, could account for the coarseness of the clastic sediments in this zone. The pollen found in these samples (K. H. Clisby, 1954, Personal communication) indicates that moist conditions prevailed until near the end of the sedimentation in this zone. The sediments contain more clastic material than ash and appear to be the result of erosion after uplift.

Zone V

Bellas Artes 37–45.3 m and Madero 37–47.5 m

The common sediment is weathered, clayey ash. Ostracods, diatoms, and sponge spicules are found throughout the zone and oolites and root holes are present at several horizons. The carbonate content is high in the lower part, and the water content is high throughout except for thin layers of either fresh ash or micro-coquina. The indications are of generally stable conditions except for short periods of volcanic activity, with shallow water to swampy conditions prevailing in the lake.

Zone IV

Bellas Artes 32–37 m and Madero 34–37 m

This rather thin zone of ashy sand shows a slightly higher degree of weathering than does Zone VI, and the carbonate content is higher throughout the sample. The pollen, although much diluted, does show that this is an interval of drier climate (K. H. Clisby, 1954, Personal communication). The carbonates also indicate this, for they are plentiful in this zone but are absent from Zone VI except in upper part, the only phase of Zone VI suggesting desiccation.

Zone III

Bellas Artes 8–32 m and Madero 8–34 m

Weathered, clayey ash carrying ostracod and diatom fossils is the typical sediment of this zone, but there are several thin fresh-ash and micro-coquina layers. There is considerable sapropel in some horizons, usually in those in which well-weathered, clayey ash is dominant. Many of these sapropel-carrying samples contain fine pyrite grains and aggregates and particles of black organic materials.

Probably the erosion of forest-covered uplands was rather slow under stable conditions; there was occasional slight volcanic activity. Lake conditions were generally shallow to swampy and at times poorly aerated.

Zone II

Bellas Artes 8–3.6 m and Madero 8–3.1 m

This zone is more varied than any below it. The characteristic type of sediment is sandy, weathered ash carrying considerable carbonate. Oolites are more abundant than in any other zone. A marl is present in both cores at around 6 m depth, and fragments of artifacts occur in several of the samples. There are fresh-ash layers at two horizons.

All these indicate low lake level and rather rapid erosion. A dry climate is suggested and some volcanic activity and possibly the effects of the activity of man with a consequent loss of vegetation, resulting in increased erosion and deposition.

Zone I

The disturbed material from the surface to a depth of 3.60 m in the 80-Bellas Artes and to 3.10 m in the 57—Madero core is here designated as Zone I. It is so distinguished in order that the upper sediments from other parts of

TABLE 6.—RELATIONSHIP OF LAKE MARGIN AND LACUSTRINE DEPOSITS IN THE CUENCA OF MEXICO

(Condensed from tables by Bryan, Zeevaert, and Foreman)

Formation	Bryan *et al* (1948)		Zeevaert (1952) Data derived from many cores in basin	Foreman (1953) Data from detailed study of two cores from central basin
	Deposits on margin of basin	Lake and marsh deposits		
Aztec and Teotihuacans Zacatenco	Alluvium and deposits with shards (dark soils on uplands)	Sands, soils, etc. with shards, peats, and clays with humus	0–6 m Sands, black and brown, clayey muds with humus and shards	Zone I 0–3 m Missing
Totoltsingo	Alluvium (dark soils on uplands)	Lake clays and peat	6–7 m Sands and dark clayey muds with humus	Zone II 3–8 m Weathered ash with some sand; marl and microcoquina at some horizons; oolites and plant root holes common; a few thin fresh pumice and brown ash layers
Caliche Barrilaco	Missing (caliche on uplands)	Assumed present in center of basin	7–8 m Clays and sand with pumice and caliche	
Sinking of lake floor				
Becerra	Upper Becerra alluvium	Sand and clay	Sands, muddy clays, pumice sand, and aquatic plant roots	
	Disconformity and caliche	Disconformity and caliche		
	Lower Becerra alluvium	Supposedly present in center of basin		
Sinking of lake floor and erosion of gullies on some slopes				
Tacubaya	(Morales Caliche on uplands)	Assumed present in center of basin	8–33 m Deposits of olive-green montmorillonite lake clays; five clay interspersed with four caliche horizons; some thin fresh ash layers	Zone III 8–34 m Weathered clayey ash; ostracods and diatoms common
	Yellow-brown alluvium (yellow-brown soils on uplands)			

TABLE 6.—*Continued*

Formation	Bryan *et al* (1948)		Zeevaert (1952) Data derived from many cores in basin	Foreman (1953) Data from detailed study of two cores from central basin
	Deposits on margin of basin	Lake and marsh deposits		
General orogeny around the basin, with erosion of wide valleys on slopes				
Tarango	Thick volcanic deposits; tufa, volcanic breccia, and pumice, etc. (no evidence of this on uplands)	Assumed present in center of basin	33–80 m Series of alluvial and lucustrine deposits; four thick sand and three clay horizons (Foreman's Zones IV and VI are same as upper two sands of this zone)	Zone IV 34–37 m Ashy sand, slightly weathered with a few horizons of well-weathered ash
				Zone V 37–47.5 m Weathered clayey ash, some thin sand beds in center
				Zone VI 47.5–61 m Ashy sand and sandy ash, little weathering or sorting
				Zone VII 61–75 m Alternating fresh and weathered ash

the valley which may not be disturbed can be correlated with this sequence of zoning. The uppermost zone studied in this paper is that named Zone II.

SEDIMENTATION

The depth of water in this part of the lake was never great, in fact, it was shallow to swampy most of the time. The criteria that point to this conclusion are the plant-root holes found at many horizons, presence of oolites dispersed throughout the cores, and the dominantly sand sediments in Zones II, IV, and VI. This continued shallowness during which 200 feet of sediments were deposited is not easily explained, for temperature and precipitation changed throughout this time. Neither subsidence nor compaction accounts for this apparent equilibrium of water level, although De Terra (1949, p. 27) does cite both of these to account for recent changes of lake level in the Tepexpan region. Although he has no positive evidence, the writer believes that the coarser, permeable alluvia on the flanks of the basin maintained the hydrostatic level. Each time the water level rose the lake expanded and extended over these permeable beds, and the movement of water down through these beds was great enough to counteract increased inflow into the lake.

Permeable beds may also explain the low content of sulphate and chlorine found in the samples. Only in the lower part of Zone VII does the water-soluble sulphate ever reach 1 per cent by weight of the dried sediment, and only in one horizon, 7.10–7.60 m of Zone II, does the water-soluble chlorine content rise to 0.5 per cent by weight. In the rest of the samples chlorine is absent except for a few

horizons in lower Zone IV, where there is a trace (0.01 per cent or less by weight). The sulphate, too, is more than 0.2 per cent by weight only in the samples at 9.4, 10.2, 20.4, 22.4, and 23.2 m depth, and in none of these does it reach 1 per cent. Drainage through the flanking permeable beds alone can account for the low percentage of water-soluble salts in the lake sediments.

The post-depositional changes that take place in a subaqueous environment are not well known. Fresh, glassy ash is found in most of the samples of these cores, even in the clay-bearing ash and in the sandy samples. Many of these particles are pumiceous and of very fine size, but are apparently fresh and unaltered. Most of the changes in the volcanic particles are pre-depositional, although the included pollen grains are invariably mineralized. This mineralization in both fresh and weathered ash is no doubt due to diagenetic processes which are active after deposition but not easily detected.

The interrelated effects of climatic change, volcanic activity, and tectonic forces on both rock and lake deposits are complex as a visit of 2 weeks to the area convinced the author. Both Bryan (1948), who studied the ancient soils of this area, and Zeevaert (1952), who has made a wide study of the cores from the lake plain, have attempted a general correlation; but neither of these authorities have carried correlation below the Becerra soil horizon. The age of younger Becerra has been limited by radiocarbon dating (Libby, 1952, p. 91) to between 11,000 ± 500 and a little more than 16,000 years. But this includes less than the upper 10 m of the lake sediments. Below that, each author recognizes a Tacubaya and next a Tarango series of deposits (Table 6).

From the study of these two cores alone it is not possible to point to any particular horizon as correlated in time with the old soils or caliches that have developed on the margins and uplands of the basin. Bryan (1948, p. 11) and also De Terra (1949, p. 29) suppose that caliche horizons which they had identified on the uplands of the basin are present in the lake sediments. Only the marl at around 5.5 m depth in the Madero core and from 5.7 to 6.1 m in the Bellas Artes core suggests this. The carbonate is very fine-grained and porous and carries oolites and ostracods in the Madero, and ostracods in the Bellas Artes core. If this can be correlated to the Caliche Barrilaco evidence at other horizons should correspond to the older caliches of the area surrounding the basin, but no other marls are found. The samples may have missed those parts of the cores representing other ancient caliches, but this is not probable, as they were examined carefully for phases of high carbonate before sampling.

The horizons which correspond in time to the development of ancient soils on the uplands are not apparent in these cores unless they are the weathered Zones III and V. The rather stable climatic, tectonic, and volcanic conditions necessary for the formation of a soil are probably those under which the clayey, weathered ash of these two zones was laid down.

The time involved in the accumulation of these sediments is uncertain. Radio-carbon dating from wood collected from the Younger Becerra formation at Ciudad de los Desportes near Mexico is older than 16,000 years (Libby, 1952), but the base of the Becerra is the same as the lower limit of Zone II in both cores of this study, that is, at the 8-m level. Table 4 shows that no extrapolation can be made from the known age of the Younger Becerra to that of the deeper layers because of the great variation in the textures, weathering, and origin of the particles in the six zones. The rate of accumulation in Zones III and V with their clays and weathered ash was much slower than that in the other zones in which fresh ash and coarse, slightly weathered sand predominate. Zone VII is unique in its rapidly alternating fresh and weathered ash layers, but there are layers of fresh ash in all zones, even in Zones III and V, where they are very thin and constitute less than 5 per cent of the total thickness of these zones.

It is evident that Zones III and V reflect rather stable times in the valley and that the time involved in the deposition of their sediments is greater than their thicknesses might indicate. The greater degree of weathering, the presence of considerable clay, and the much higher pollen concentration in these two zones

indicate that the area not only was without any strong volcanic or tectonic activity but also had a good vegetation cover of forest trees—pine, oak, and fir being the common varieties. Such a vegetation would protect the mantle from rapid erosion even on the upper slopes and allow time for weathering to form considerable clay. This continued presence of forest cover during the deposition of these weathered clayey ash zones indicates that rainfall was adequate and that temperature variation was limited to maintain such stability. An evaluation of the vegetation and attendant climate and of changes in climate is outside the scope of this paper but will be discussed by the palynolygists who are reporting on these sediments in other papers. It is significant that, where climatic factors are similar, the time needed to develop a soil on ash and porous lava flows is short compared to that needed to develop a soil to a similar stage on dense rock.

Correlation

The sediments deposited in a high intermontane basin are by their very origin isolated from similar deposits of the same age, even in the same physiographic province. If correlation is to be made it is necessary to establish either a direct time relationship, a pattern of sedimentation that is a response to widespread but changing conditions, or a similarity of biologic content and variation for correlation in biostratigraphic units.

Radiocarbon dating is insufficient; evidence from the sediments themselves is based on variations caused by volcanism, tectonic activity, and climate. The first two of these forces are very indicative in the basin but of little value for correlation outside this area. This is partly due to short length of time, in the geological sense, represented by these deposits and partly to the limited extent, in both time and space, of the individual volcanic and tectonic paroxysms in this region.

Two problems of correlation arise from this study: the first is the relationship between the lake deposits and the ancient soils found on the lower slopes of the basin; the second is the broader problem of correlation with other lake or swamp sediments outside this province.

A soil can form only when a vegetation cover is adequate and the slope of the terrain is such that the mantle is held in a fairly stable condition long enough for the biota and the processes of weathering to affect it sufficiently (Bryan and Albritten 1943, p. 471). These conditions will be reflected in the lake sediments which will be clay and weathered particles of ash and detritals mixed with chemical precipitates and organic remains.

Burial and preservation of a soil will result when the accumulation of sediments is too rapid for the soil-forming processes to continue or when a lava flow covers a soil. The effects of a lava flow on the slopes above the lake may not be apparent in the lake sediments, but the burial of a soil by ash or detritus would cause a radical change in the rate and type of sedimentation.

When erosion is increased to such a degree that the soil is carried away, a rapid deposition of mixed soil and detrital particles will probably take place in the lake.

On the slopes above the lake, soil formation, burial, and destruction have occurred during the deposition of these sediments. Since in any given locality the soil is fundamentally the result of climate acting through sufficient time under suitable conditions of weathering, erosion, and deposition, it follows that a soil will normally cover a considerable area, although in a mountainous region like the Mexico City basin it will change with altitude which affects vegetation and rainfall. Burial or destruction, on the other hand, may be either local or widespread. In a region such as this, where volcanoes are common, soils may be buried and destroyed in one part by ash fall and its accompanying processes of deposition and erosion, while normal soil formation may be proceeding in the rest of the region. These variations will also be reflected in the sedimentation of the lake, and if any large area of vegetation is destroyed by the ash, the pollen content of part of the lake deposits will vary in both amount and kind until the vegetation again is stabilized.

Widespread changes in soil formation, in erosion, and also in deposition may result either from radical climatic changes or from tectonic activity. The latter, however, probably

will not act with sufficient rapidity and severity over large enough an area to affect the sedimentation significantly. Since the beginning of the Pleistocene great and widespread climatic changes have frequently occurred, and these have impressed both sedimentation and vegetation and consequently the pollen found in the sediments. The minerals and the organic content of Pleistocene and later sediments give evidence that may be used in correlation and which, when correctly interpreted should also lead to a clearer picture of these climates and their fluctuations.

The broader problem of correlation with other lake and swamp areas has been initiated (Sears and Clisby, 1952), but only a beginning has been made. So far, very few petrographic and pollen analyses of deep cores have been made. Work is at present being done on a deep core from the San Augustin Basin, New Mexico, by the Department of Geology of Oberlin College and the Conservation Laboratory at Yale University, under the direction of Professor Paul B. Sears.

Conclusions

Throughout both the cores from Mexico City, fresh ash is interspersed with weathered ash, detritus, and authigenic sediments, and it has been possible to divide these sediments into seven zones, similarly numbered in each core and almost identical in thickness, mineral composition, fossil content, and water-holding capacity.

Montmorillonite clay is present in the weathered zones and is without doubt the result of subaerial weathering and not of diagenetic changes since no clay is found in any of the fresh ash layers. The zones carrying the clay and weathered particles are the result of rather stable conditions when the surrounding slopes were forest-covered and the mantle was held in place under humid conditions for a sufficiently long time to permit extensive weathering and formation of considerable clay.

The fresh ash is partly the result of immediate wind transportation and partly the result of short time deposition on the slopes above the lake before being carried by water and wind into the lake. It seems, too, that this ash was at times of sufficient depth to destroy the vegetation; when this happened rapid erosion of both the freshly laid ash and the underlying weathered mantle brought mixed deposits of fresh ash and weathered detritals into the lake.

A record of changing climates has been established, in part from a study of the textures, minerals, and structures of these deposits but chiefly from the contained fossil pollen. The plants have obviously been sensitive to climatic change throughout the entire time represented by these cores. Variations in temperature and precipitation, when sufficiently severe to change the plant assemblage from the abundant cover of a humid forest to the sparse cover of xerophytic desert plants, affect the textural pattern and degree of weathering of the sediments. Similarly, when tectonic activity has been severe enough to cause the rivers to initiate a fresh cycle of dissection a change from well-weathered finer sediments to slightly or unweathered poorly sorted coarser ones has occurred. Without the help of the pollen analyst it has not been possible to differentiate between the changes in sedimentation brought about by desiccation and those brought about by tectonic activity. But where the indicated changes have occurred in the sediments, and the pollen shows that the climate has remained humid, then it is assumed that the cause was tectonic. However, where these changes in sedimentation have occurred, and at the same time the pollen has shifted from that of a humid to that of an arid plant assemblage, then it is inferred that climate was the cause for these changes.

It was stated earlier in this paper that this study was undertaken to find out to what extent the record of the sediments would be of help to the paleobotanist and paleoclimatologist. Mrs. K. H. Clisby and Professor Paul B. Sears, who have worked on these phases of this study, are convinced that a knowledge of the sedimentation is necessary to a correct interpretation of past plant assemblages and climates. It is obvious to the writer that when the fossil pollen is studied along with the sedimentary record a much more accurate account of the conditions of sedimentation can be given and better evaluation of the causes that give rise to variations in the sediments

made than when the pollen record is not known.

These studies point up the interdependence of results where the study of a complex problem is undertaken by more than one discipline. The data and interpretation gained from each science clarify and help to form a more complete picture of the history of the region than can be gathered from a single approach by one discipline alone.

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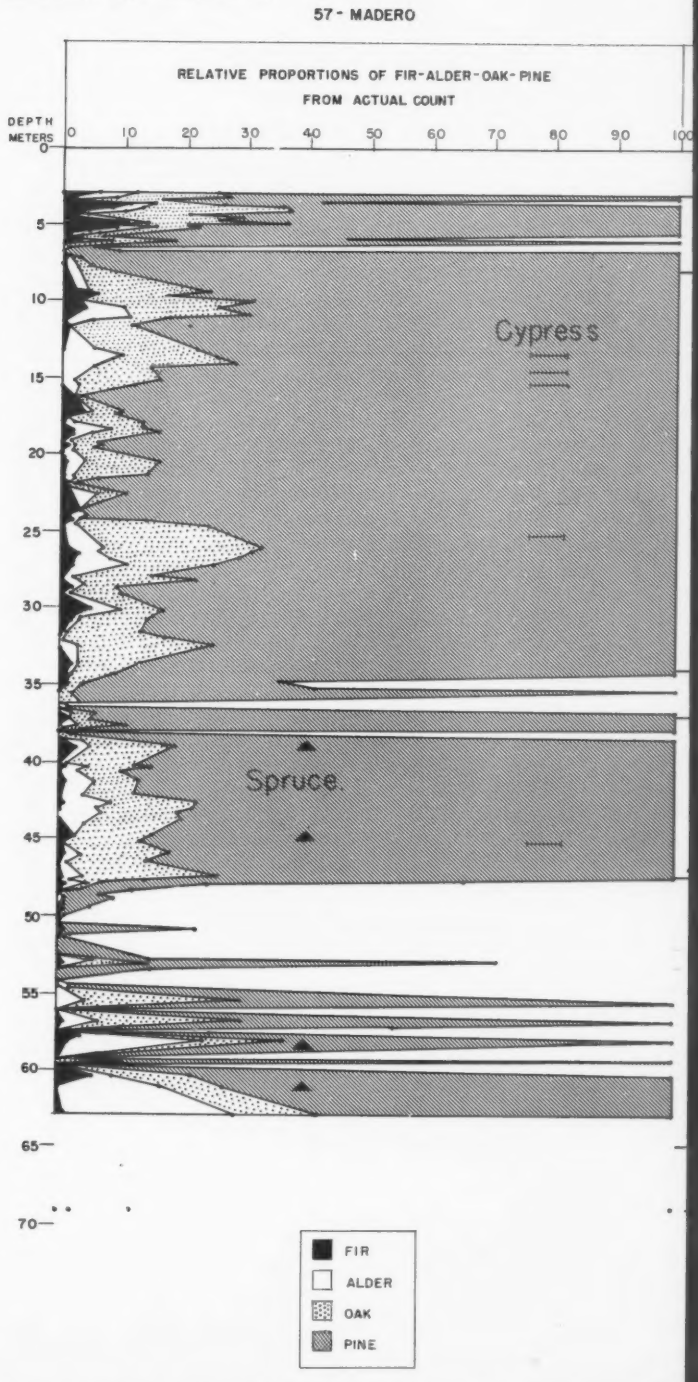
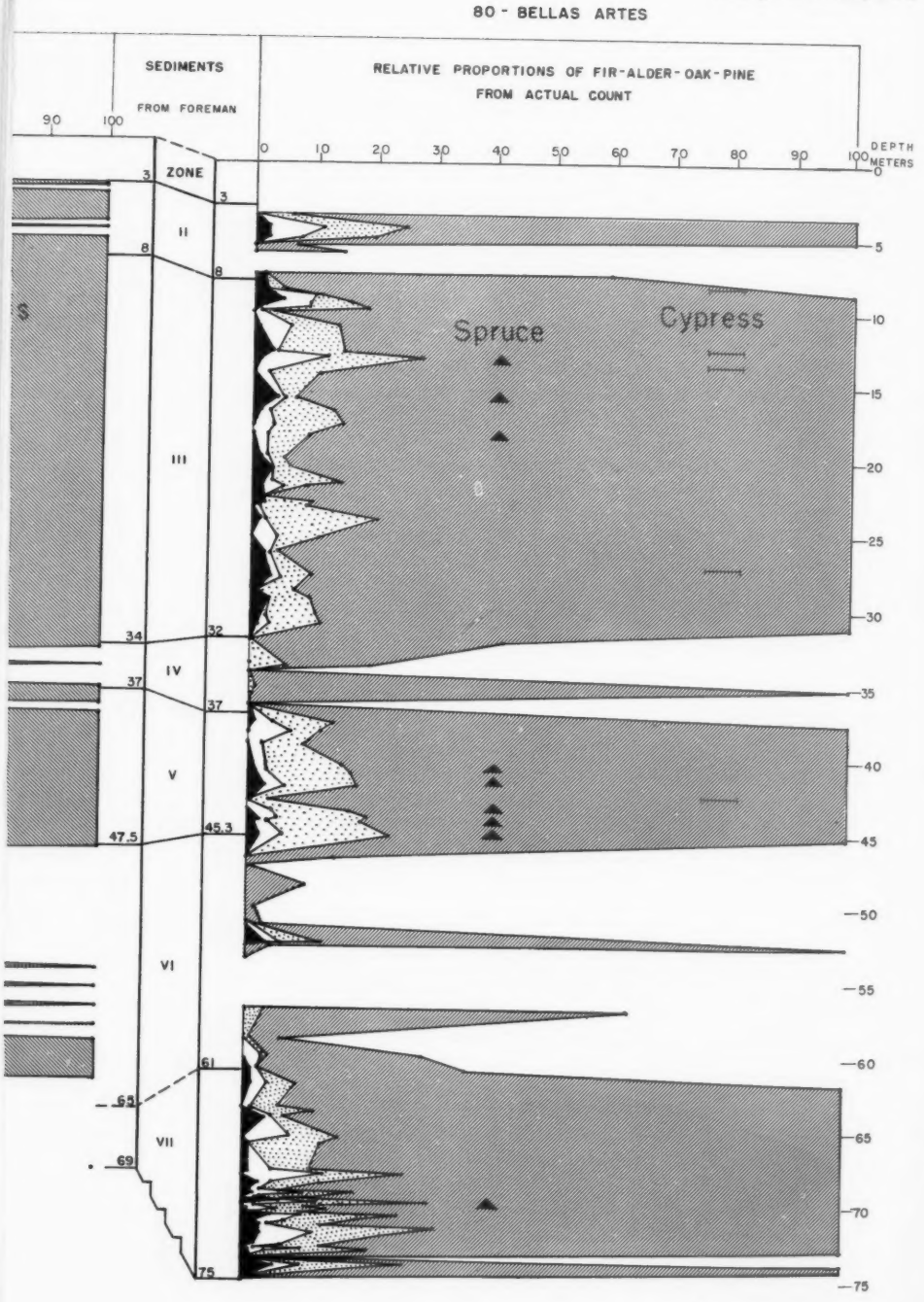


CUMULATIVE HISTOGRAM OF UPLAND FORE



FOREST POLLEN IN RELATION TO SEDIMENTARY ZONES

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PALYNOLOGY IN SOUTHERN NORTH AMERICA

PART III: MICROFOSSIL PROFILES UNDER MEXICO CITY CORRELATED WITH THE SEDIMENTARY PROFILES

BY KATHRYN H. CLISBY AND PAUL B. SEARS

ABSTRACT

The sediments of the Cuenca de Mexico fall into two classes—transported materials from the surrounding highlands and residual materials deposited as a result of limnological processes, *in situ*. The latter include inorganic and organic constituents as well as microfossils. Studied together these components reflect events influenced or controlled by changing climates, by volcanic and tectonic activity, and by erosion whether natural or accelerated by man.

Changes in percentage composition of upland forest pollen reflect changes in available moisture, and thus in climate. Changes in the density or abundance of recoverable pollen are closely related to changes in sedimentary zones and in water content of the sediments. High pollen density is associated with slow sedimentation and high water content of the sediments, whereas stages of rapid sedimentation and low water content are marked by sparseness or absence of pollen. As upland forest pollen composition is chiefly a function of climate, pollen density is a function of volcanic and other physiographic processes.

Pollen and spores from lowland communities reflect swamp conditions and changes in vegetation caused by disturbance of habitat by volcanism, tectonic activity, and human occupation. Temporary disturbance from fresh ash fall and tectonic activity tends to be followed by a brief period of heavy density of ruderal pollen (composite, amaranth, grass) and by prompt restoration of the prevailing upland forest communities.

Maize pollen was recovered throughout the archeological period and at a depth of 9 m, predating the presence of agricultural man in the basin. It was again recovered at 70 m, a depth which represents considerable antiquity for maize; which is evidence in favor of the American origin of this plant.

Contemporary pollen gathered from a site comparable to the Mexico City basin indicates relatively short distance of upland pollen transport. Therefore, the sparse spruce pollen found at various horizons in the Mexican cores probably came from the vicinity during times cooler than the present. Exceptionally heavy spruce pollen in samples from a recent horizon appears to be the result of redeposition of older sediments from the surrounding highlands.

Correlation of the sedimentary components involves a complex of climatic, tectonic, volcanic and biotic factors; evidence from every possible source, in addition to conventional pollen analysis, is required for proper interpretation.

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Introduction

The Cuenca de Mexico, discussed by Zeevaert (1951; 1953a; 1953b) and Foreman (1955), is one of the earliest centers of an agricultural civilization in the Americas. Evidence of human artifacts in association with the mammoth (Aveleyra *et al.*, 1952) and the finding of Tepexpan Man (de Terra *et al.*, 1949) place hunting man in the Cuenca along with the mammoth. With such a rich history of the recent past afforded by archeological sites and by the deep unconsolidated sediments in a basin of pre-Pleistocene origin, the Cuenca offers an ideal site in which to study the climates of the Pleistocene.

The object of this study has been to obtain a record of changing climate with the use of pollen analysis to determine the vegetation which reflects these changes. The first paper of this general series (Sears, 1952) applies this method to the upper or archeological levels in the Cuenca de Mexico and shows past changes of climate sufficiently powerful to affect the patterns of human culture. A subsequent brief report (Sears and Clisby, 1952) shows that major climatic sequences in Mexico and New Mexico are essentially similar and makes clear another possibility of continuous sedimentary records far beyond the glacial ice margin.

Two parallel cores—Bellas Artes and Madero—have been described by Zeevaert (1953b) and Foreman (1955). These appear to represent the longest time interval of any profiles yet reported from high altitude intermontane basins. Frey (1953, p. 312) suggests that his low-altitude pollen profiles from the Carolina Bays area may extend into the early Wisconsin, while cores from sea bottom represent even greater lapses of time. L. R. Wilson (unpublished) has analyzed at 30-foot intervals several cores from the Gulf of Mexico, which may extend through the Tertiary. Most of the profiles in the literature represent more limited spans of post-glacial or interglacial time. Most of them, too, present relatively simple problems of separating and concentrating the microfossils, since much of the sediment is highly organic; even the dominantly inogranic clays, silts, and sands are not unduly resistant to treatment.

The sediments of the Cuenca de Mexico, however, are complex and present difficult analytical problems. They are volcanic in origin, and the pollen and spores have apparently mineralized.

Fossil pollen studies aim primarily at getting a record of changing composition of prevailing forest communities, which are assumed to be climatically controlled. Much, however, may be learned by study of the nonforest pollen and of that which—whether from woody or herbaceous plants—reveals edaphic influence. For this reason, the latter types have been studied in considerable detail in the present paper. Included among them have been the pollen of maize and its close relatives (Barghoorn *et al.*, 1954).

Particular attention has also been given to the abundance or scarcity of pollen as such, *i.e.*, pollen density patterns. These show that a close correlation exists between the sedimentary zones as determined by petrographic analyses, by mechanical characteristics of the sediments, and by the pollen density.

Two basic problems exist in pollen analysis; recovery of pollen from sediments, and the climatic interpretation of the pollen diagram, the latter discussed under Pollen Profiles. Conditions of sedimentation and character of the sediments are closely interrelated.

Recovery of pollen from the volcanic sediments in the Cuenca de Mexico and from the San Augustin Plains and the Valle Grande (the latter two in New Mexico) presents difficult chemical problems. Established techniques used for pollen concentration from bogs and lakes formed after the ice retreat in northern areas can be applied only in part and with modifications. The flotation method of Frey

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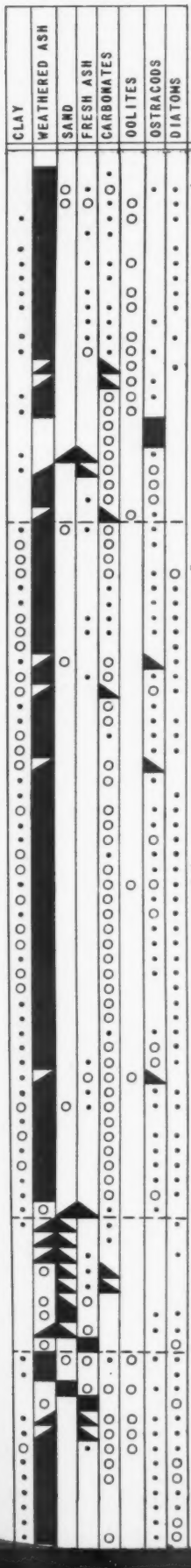
TABLE 1. POLLEN ANALYS



DEPTH-Meters	FOREST POLLEN DENSITY	COUNT	PINUS	ABIES	PICEA	QUERCUS
3.10	512	100	75	6		12
3.30	102	100	73	2		18
3.50	44	43	26			16
3.70	108	100	72	11		11
3.90	330	100	64	8		23
4.10	286	100	64	3		26
4.30	242	100	80	4		15
4.50	220	100	71	1		24
4.70	328	100	75	5		17
4.90	382	100	64	11		22
5.00	180	100	80	4		13
5.10	131	100	78	4		7
5.20	218	100	80	9		8
5.40	170	100	86	4		9
5.60	218	100	93	2		4
5.80	46	46	40	1		5
6.00	160	100	82	3		10
6.20	9	9	9			
6.40	5	5	4			1
6.60	10	9	9			
6.80	200	100	100			
7.00	270	100	99	1		
7.40	256	100	96			2
7.85	270	100	94	2		3
9.37	3060	100	76	2		20
9.56	3060	100	83	6		11
9.93	1000	100	69	3		28
10.31	2300	100	75	4		15
11.00	1840	100	70	2		19
11.20	1540	100	83			12
11.60	1150	100	89	1		10
13.07	1530	100	79			16
13.64	3093	100	75			15
14.02	4600	100	72			23
14.21	1040	100	86			9
15.07	1340	100	84			14
15.45	1535	100	88			9
16.21	1835	100	97	2		1
17.21	3066	100	90	4		5
17.43	3040	100	92	1		6
17.86	1850	100	87			11
18.29	1830	100	87	2		5
18.53	1830	100	84	2		11
19.34	1205	100	94			5
19.37	1840	100	93	1		5
19.55	1060	100	95			5
20.39	1530	100	84	1		12
21.37	1240	100	86			12
21.56	2300	100	94			4
21.75	1840	100	98	1		1
22.13	2300	100	95	1		4
22.51	1530	100	89	1		5
23.64	2300	100	97	3		
23.85	4600	100	96	1		3
24.27	1840	100	86	2		11
24.63	1150	100	76			22
26.13	1530	100	67	1		26
26.40	990	100	69	3		25
26.82	3303	100	71	2		21
27.24	2300	100	75	2		14
27.95	1129	100	85			13
28.18	3066	100	83			14
28.59	4500	100	91	2		5
29.00	1845	100	90	3		6
30.05	3679	100	83	5		7
30.48	3030	100	85	2		12
30.83	1860	100	86	2		11
31.55	2770	100	87			12
31.97	1830	100	83			17
32.39	2000	100	75			22
33.60	1150	100	87	2		10
34.16	210	100	91	1		7
34.61	36	36	32	1		2
35.05	42	42	40	1		1
35.25	200	100	98			2
35.60	4	4	4			
36.18	3	3	3			
36.40	1	1	1			
36.83	665	100	94			4
37.21	182	100	95	2		3
37.73	1150	100	89			8
37.92	2300	100	96			4
38.11	0	0				
38.52	512	100	98			2
38.63	1830	100	90	1		6
38.82	1835	100	83	2		13
39.01	2290	100	81	2	1	14
40.32	3080	100	88			11
40.33	2960	100	85	1		10
40.53	2320	100	90			7
41.31	3060	100	87	1		7
42.11	3060	100	88			8
42.74	1160	100	77	1		15

EN					NON-FOREST POLLEN											
ABIES	PICEA	QUERCUS	ALNUS	OTHERS	NON-FOREST POLLEN DENSITY	COUNT	SALIX	ILEX	GRAMINEAE	COMPOSITAE	AMARANTACEAE	SPORES	HIGHER AQUATICS	UNIDENTIFIED	TAXODIUM	MAYDEAE
6		12	7		743	147	1	5	9	12	14	28	7	3		68
2		18	7		154	214	5		18	15	30	36	10	11		89
		16		1	58	54			28	2	12	4	4	2		2
11		11	4	2	126	112			25	21	21	34		11		
8		23	5		365	111			15	7	11	14		3		61
3		26	7		514	177	3		17	9	29	22	15	4		78
4		15	1		480	106	1		15	5	9	20	2			54
1		24	4		411	187	2		24	44	43	12	4	9		49
5		17	3		373	114			15	5	15	15	2	5		57
11		22	3		452	117	1		6	12	37	12	3	1		45
4		13	3		254	202	4		16	15	60	23	5	3		76
4		7	11		358	240			40	66	80	28		6		20
9		8	3		268	122			20	11	43	16	3	1		28
4		9	1		105	67			11	2	15	7		8		24
2		4	1		60	27			6		5	5	3			8
1		5			72	72			21	4	14	4				29
3		10	5		140	88			14	2	14	14		1		43
					3	3			2							1
		1			0	0										
				1	0	0										
					0	0										
1					8	3			3							
		2	2		0	0										
2		3	1		6	2								2		
2		20	2		50	5			5							
6		11			50	2			1					1		
3		28			85	9	1		4	2	2					
4		15	6		125	6			4	2						
2		19	9		80	9			3	2	2		1	1		
		12	5		230	16			7	2		5	2			
1		10			105	9			2	2	2	2		1	0	
		16	5		105	7			2	3		2			A	
		15	10		373	13			4	5	1	2		1	A	
		23	5		782	17			10			4	2	1	O	
		9	5		95	12			4	5			2	1	O	
		14	2		92	9			1	4	2	1		1	A	
		9	3		15	1				1					A	
2		1			0	0										
4		5	1		54	2			2							
1		6	1		140	4			2	1	1					
		11	2		95	6			3	2	1				A	
2		5	6		40	2			1		1					
2		11	3		60	3	1		1		1					
		5	1		125	17			4	9			1	3	M	
1		5	1		240	13			9	4						
		5			280	10						10			A	
1		12	3		130	8			1	1		3		3	M	
		12	2		30	24			14	4	2	3		1		
		4	2		23	7			1		3	3			O	
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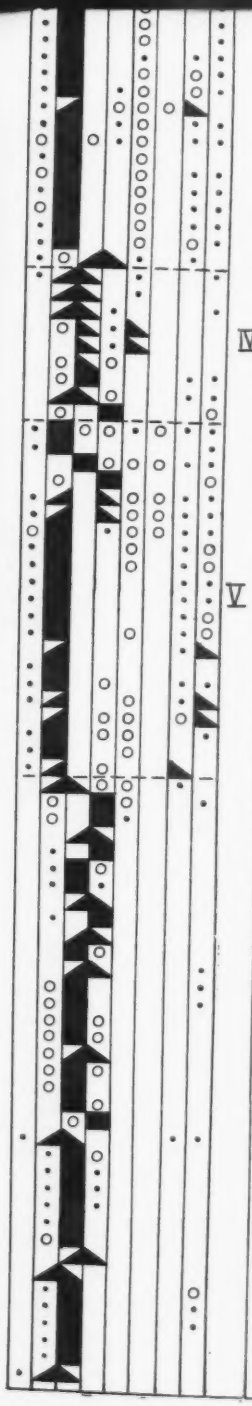
1		4			460	20			4		1		15			
1		5	5		45	3			1					2		
3					25	1			1							
1		3			50	1			1							
2		11	1		95	5			3	1	1					
		22	2		80	7			7							
1		26	6		155	10			8	2						
3		25	3		268	13	1		4	1		1		6		
2		21	6		296	10			3	3				4		
2		14	9		780	16			5	7	1			3	2	
		13	2		226	9							3	6	4	
		14	3		277	9			5	3	1					
2		5	2		150	4			2	1			1			
3		6	1		180	20			7	1		1	2	9		
5		7	5		441	24	1		10	1	4		2	6		
2		12	1		295	8			1	2	2		2	1		
2		11	1		70	4			3		1					
		12	1		277	10			8	1	1					
		17			610	38			18	8	4		5	3		
		22	3		250	11			8	3						
2		10	1		305	27	2		16	2			4	3		
1		7	1		33	16			8		2		4	2		
1		2		1	2	2			1					1		
1		1			3	3			2			1				
		2			28	14			5		1	6		2		
					0	0										
					1	1			1							
					1	1			1							
		4	2		765	117			49	8	28	11	21			
2		3			35	18	1		6	1		5	1	4		
		8	3		320	33			20	2	5	5		1		
		4			215	26			16	3	3	3	1			
					0	0										
		2			25	5			2			3				
1		6	3		125	7			2		1	4				
2		13	2		150	8			5			3				
2	1	14	2		700	17			7	3		2	4	1		
		11	1		320	11			7	2		1		1		
1		10	4		470	17			8	1	1	2	3	2		
		7	3		80	4			4							
1		7	5		310	10			8	2						
		8	4		210	7				2	2	1		2		
1		15	7		105	10			4	3	1	2				



24.63	1150	100	76	1	
26.13	1530	100	67	3	
26.40	990	100	69	2	
26.82	3303	100	71	2	
27.24	2300	100	75		
27.95	1129	100	85		
28.18	3066	100	83		
28.59	4500	100	91	2	
29.00	1845	100	90	3	
30.05	3679	100	83	5	
30.48	3030	100	85	2	
30.83	1860	100	86	2	
31.55	2770	100	87		
31.97	1830	100	83		
32.39	2000	100	75		
33.60	1150	100	87	2	
34.16	210	100	91	1	
34.61	36	36	32	1	
35.05	42	42	40	1	
35.25	200	100	98		
35.60	4	4	4		
36.18	3	3	3		
36.40	1	1	1		
36.83	665	100	94		
37.21	182	100	95	2	
37.73	1150	100	89		
37.92	2300	100	96		
38.11	0	0			
38.52	512	100	98		
38.63	1830	100	90	1	
38.82	1835	100	83	2	
39.01	2290	100	81	2	1
40.32	3080	100	88		
40.33	2960	100	85	1	
40.53	2320	100	90		
41.31	3060	100	87	1	
42.11	3060	100	88		
42.74	1160	100	77	1	
42.95	1140	100	77		
43.37	925	100	78		
43.79	930	100	80		
44.77	765	100	85	2	1
45.19	1150	100	87	1	
46.04	1830	100	82	1	
46.47	660	100	86		
47.53	1140	100	74	1	
47.72	66	66	52		
47.91	24	24	17	1	
48.42	13	13	10		
48.61	7	7	7		
48.71	9	9	8		
49.68	3	3	2		
49.89	1	1	1		
50.59	0	0			
50.93	22	22	21		
51.12	2	2	2		
51.31	0	0			
52.86	15	15	15		
53.03	71	71	56	1	
53.31	15	15	14		
54.00	0	0			
54.23	0	0			
54.35	2	2	2		
54.46	1	1	1		
54.63	2	2	2		
55.20	0	0			
55.40	0	0			
55.60	1530	100	70		2
56.11	0	0			
56.92	256	100	68	1	2
57.45	56	56	42		1
57.56	0	0			
57.73	24	24	12		
58.18	306	100	61	2	1
59.19	0	0			
59.60	2626	100	89		1
59.80	0	0			
60.01	2	2	2		
60.40	208	100	76	2	3 1
61.10	176	100	73		1
62.85	?	100	58	1	1
69.05	770	100	86		1

■ Dominant:

◢◣ Two elements make up greater part of sediment.

○ Component import diagnostically great in amount.

• Present but not

76			22	2			80	7			7									
67	1		26	6			155	10			8	2								
69	3		25	3			268	13	1		4	1			1		6			
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75	2		14	9			780	16			5	7	1				3	2		
85			13	2			226	9								3	6	4		
83			14	3			277	9			5	3	1							
91	2		5	2			150	4			2	1				1				
90	3		6	1			180	20			7	1			1	2	9			
83	5		7	5			441	24	1		10	1	4			2	6			
85	2		12	1			295	8			1	2	2			2	1			
86	2		11	1			70	4			3		1							
87			12	1			277	10			8	1	1							
83			17				610	38			18	8	4			5	3			
75			22	3			250	11			8	3								
87	2		10	1			305	27	2		16	2				4	3			
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3							1	1			1									
1							1	1			1									
94			4	2			765	117			49	8	28	11	21					
95	2		3				35	18	1		6	1		5	1	4				
89			8	3			320	33			20	2	5	5		1				
96			4				215	26			16	3	3	3	1					
							0	0												
98			2				25	5			2			3						
90	1		6	3			125	7			2		1	4						
83	2		13	2			150	8			5			3						
81	2	1	14	2			700	17			7	3		2	4	1				
88			11	1			320	11			7	2		1		1				
85	1		10	4			470	17			8	1	1	2	3	2				
90			7	3			80	4			4									
87	1		7	5			310	10			8	2								
88			8	4			210	7				2	2	1		2				
77	1		15	7			105	10			4	3	1	2						
77			16	6	1		225	19			5	7	1	2	2	2				
78			12	7	3		180	19			8	4		6	1					
80			16	4			150	17			9	4	1	3						
85	2	1	12				60	8			3	1	1	2		1				
87	1		12				160	14			7	3		4				A		
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56	1		9	5			41	42			16	1	4	19	2					
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0			25	5			1870	101			41	6	34	18	2					
							0	0												
8	1		23	6	2		86	29		3	6	5	1	4	5	5				
2			10		4		34	34			4	10	20							
							0	0												
2			4	8			12	12				6	2			4				
1		2	14	21	2		141	46	2		1	27	4	1	8	3				
							0	0												
9			11				7941	336			34	5	271	13	10	3				
							0	0												
2							30	30			2				28					
6	2	3	13	3	3		119	57			8	27	8	3	7	4				
3			10	17			40	24	1		14	6	2	1						
8	1		14	27			?	99	1		49	8	3		30	8				
6			12	2			58	8			4	3	1							

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O - Occasional
A - Abundant
M - Moderate

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(1952, p. 519) could not be used because of the increased specific gravity of the pollen. Pollen separation from these volcanic sediments requires chemical treatment that will dissolve the minerals and leave the pollen intact.

In the Cuenca de Mexico both the allogenic and authigenic materials are important in the fossilization and preservation of the pollen grains *in situ*, and in their resistance to destruction by chemical treatment during concentration of the pollen.

Petrographic analysis of the Bellas Artes and Madero cores by Dr. Foreman has contributed significantly to the knowledge of the geological events of the area. In addition, it serves to simplify chemical procedures used in pollen concentration, to distinguish between phases of slow and rapid sedimentation, and to identify zones of volcanic and tectonic activity. Sharp decreases in pollen density at certain horizons may be due to dilution and/or maceration of the pollen grains during stages of rapid deposition, or to forest depletion from desiccation or fire.

The distance of pollen transport by wind and the degree of preservation of pollen in soils are widely debated. For critical evaluation of the pollen profiles from under the City of Mexico, some of the results are included from studies now under way in the San Augustin Plains of New Mexico. This site is comparable topographically to the Cuenca de Mexico in that it is a high altitude, intermontane, undrained volcanic basin. The annual precipitation of less than 13 inches is similar to that of the northeast section of the Cuenca de Mexico. Unlike the Cuenca, the summer and winter temperature range is wide and the playa surface is undisturbed by agriculture, although it has been highly over-grazed. The valley floor is at present sparsely occupied by chenopods, occasional amaranths and composites, and scattered clumps of gramma grasses. Juniper dots the foothills, and oak is found in the protected ravines. Pinon pine replaces juniper at slightly higher elevation, and it is replaced in turn by ponderosa pine farther up the mountain slopes. At still higher altitudes ponderosa pine is found mixed with limber pine (*Pinus flexilis*), whereas quaking aspen occupies sites disturbed by land slides and fire. At even higher altitudes the forest consists of fir and limber pine with scattered spruce in the ravines.

The air distance of pinon pine is about 6 miles from the center of the playa, ponderosa pine about 7 miles, limber pine and fir around 8 miles, and spruce nearly 20 miles. Pollen was not recovered from the upland forest soils but was found in the surface soils of the playa. Pinon pine composed over 90 per cent of the forest pollen in such surface material collected in 1952. There were a few pollen grains of ponderosa pine, a rare grain of limber pine, extremely rare fir, and no spruce pollen. Junipers are nearest the playa but their pollen was not found.

Although this evidence is limited, it does show that the distance of pollen transport for some genera can be measured in the San Augustin Plains, and it further indicates the short distance of pollen transport in an intermontane basin. Additional studies on the distance of pollen transport in the area are being considered. These should involve plotting the abundance and distribution of the individual forest species in relation to pollen transport.

Unfortunately, the surface soils and upper 3 m of the sediments in the Cuenca de Mexico are greatly disturbed by cultural practices. Therefore, the writers can only suggest that forest pollen transport in the Mexican basin has the same limitations as in New Mexico. However, the distance of pollen transport as well as wind lift for Indian corn (*Zea Mays*) has been studied in several areas under different conditions of wind velocity and varying topography (Jones, Personal communication). These studies indicate an extremely limited dispersal range for maize pollen.

Unlike pollen patterns from northern bogs where generic changes in forest trees are climatic indicators, the pollen from the Mexican and New Mexican basins exhibits no marked generic changes from the present forest flora other than the occurrence of spruce pollen in the deposits of the Cuenca de Mexico. Here the appearance of spruce at intermediate and lower levels, although scant and sporadic, may be taken as evidence of temperatures generally lower than those of the present.

Spruce (*Picea chihuahuaensis* Martinez) is not known today nearer than Chihuahua and Durango, where it occurs at 2300–2500 m (Martinez, 1953, p. 9). Some critics may feel that spruce pollen represents long distance transport from outside the area, but in one shallow drilling from the corner of Reforma and Versalles streets in Mexico City, 3 m below the street surface, spruce pollen was found to compose 68 per cent of the total forest pollen. The sediments, according to Foreman, seemed to indicate redeposition by a turbidity current or a mud flow. Consequently, those samples containing a high percentage of spruce pollen were probably redeposited from an upland lake or mountain tarn. This finding confirms the former presence of spruce in the mountain environs of Mexico City rather than long-distance transport by wind, for it appears unlikely that 68 per cent of the forest pollen could be wind-borne contamination from areas at great distance outside the Cuenca.

Acknowledgments

The writers are indebted to Engineer A. R. V. Arellano for his untiring efforts and insistence that the climatic and geological history of the Cuenca de Mexico be founded on scientific evidence. Professor L. R. Wilson helped immeasurably by his counsel on pollen identification and methods for pollen concentration, as well as by unlimited access to his personal files of unpublished data. Sincere appreciation is extended to Professor P. C. Mangelsdorf for his unfailing interest and to Professor E. S. Barghoorn for identification of pollen grains from the tribe Maydeae. Professor Frederick Grover contributed generously of his time and counsel. Without the close collaboration of Professors Leonardo Zeevaert and Fred Foreman this paper would have been impossible. Thanks are expressed to Dean Blair Stewart for encouragement and support of this study at Oberlin College. Acknowledgments are also due the Instituto Geologico's Seminario Para Estudios Cenozoics, The Geological Society of America, The Wenner-Gren Foundation, The Willys-Overland Inc., and P. J. Clisby for generous aid.

Method of Study

General Statement

The outer wall or pollen exine is very resistant to processes of nature and the laboratory. If the initial conditions of a deposit are favorable, pollen may be preserved in it almost indefinitely. This accounts for our ability to recover it from pollen-bearing sediments even when severe chemical treatment is required. However, no pollen spectrum is a complete reflection of the vegetation from which it came, and no pollen profile a detailed record of all changes in vegetation. Many plants, being insect-pollinated, produce scant and sticky pollen, which seldom finds its way into contemporary sediments. Fortunately, the dominant vegetation is usually wind-pollinated species whose pollen can be preserved in and later recovered from suitable sediments. Conditions of sedimentation (weathering, erosion, and diagenetic changes) control the preservation and concentration of pollen, while the character of the sediments determines the means of subsequent recovery and analysis in the laboratory. Increase in specific gravity of the preserved pollen is an additional consideration.

In the Cuenca de Mexico the sediments are largely composed of fragments of lava and ash, usually of andesitic rocks, which show varying degrees of weathering and erosion. At some horizons iron oxides as well as organic matter are common, and frequently these form aggregates in which the pollen grains are trapped. In weathered ash and clay samples, water- and alcohol-soluble materials should first be removed, and the residue treated with hydrofluoric acid to drive off silica as a tetrafluoride. Wilson's modification (Personal communication) of Erdtman's (1943, p. 27) acetolysis method serves partially to break up some of the aggregates as well as to acetolyze the residue. Further agitation and bleaching can be secured by adding crystalline potassium chlorate to the hot acetolyzed mixture. Cellosolve (ethylene glycol monoethyl ether) clears the pollen grains and facilitates identification. Dense jells, following hydrofluoric treatment in marls and ostracod microcoquinas, were

precipitated in ammonium hydroxide, and the precipitate dissolved in nitric acid. Pollen concentrations in sediments composed of fresh ash or sand could not be increased following hydrofluoric acid treatment. All residues were mounted on slides in safranin-stained glycerine jelly.

Pollen Count

Pollen and spore grains were counted under a binocular microscope using a 10 × eyepiece and 16 mm objective. For identification of individual grains, 1.8 mm and 1.0 mm objectives were used. Wherever possible, counting was continued until 100 grains representing the upland forest (pine, oak, alder, fir, spruce) had been tallied, and the percentages of each then read directly. The accompanying pollen of other—usually valley and edaphic—vegetation was therefore read as so many nonforest pollen per 100 forest pollen. The pollen of certain trees of the valley, notably cypress and willow, has been included as nonforest pollen.

Where fewer than 100 forest pollen occurred on 2 slides, all grains on the area of 22 mm x 80 mm (or 1760 sq. mm) were counted and the absolute counts entered in the tables. To obtain comparative abundance, or pollen density, the number of pollen to be expected in an area of 1760 sq. mm was calculated for every sample. This gives a rough but usable comparison which is confirmed by study of the accompanying sediments.

Identification of Pollen

Cain (1948) and others have used size-frequency curves to identify pollen species, but in these cores such measurements were not feasible for in some layers the grains were obviously shrunken and in others greatly inflated because of the varied effect of preservation and chemical treatment on pollen size. Therefore, the tree pollen grains and in general the nonforest pollen and spores were recorded only by their generic names. However, in a few instances, distinctive exine sculpture patterns identified the species. Pollen of maize, teosinte, and Tripsacum have been identified by Elso S. Barghoorn and Margaret Wolfe. Dr. Barghoorn has established a method for identification of these morphologically similar grains by using "... a comparison of the ratio in size which exists between the pore (including the annulus) of the pollen grain and that of its long axis." (Barghoorn *et al.*, 1954, p. 232). This work by Barghoorn and Wolfe has taken well over a year, and illustrates the need for co-operative research in identifying these microfossils.

Species identification of the Mexican pines would have given valuable climatic information, but so far this has not been possible. Identification of ostracods and diatoms would also shed more light on lake depth by separating the fossil species into fresh and brackish water groups.

Pollen Profiles

In studying the upland pollen the ecological interpretation of Deevey (1944, p. 142) and Sears (1952, p. 244) is used. In some zones pine, in comparison with oak, alder and fir, reaches relatively high values (88 per cent or more); in alternating zones pine declines in importance. Since the other three genera require relatively more moisture than pine, the record is then one of alternating moist and dry periods. The two cores, 250 m apart, have similar records, although the rates of sedimentation in the two are slightly different. Spruce pollen occurs infrequently but is grouped at definite horizons in the cores.

Fir and alder doubtlessly indicate more moist conditions than does pine. The less obvious relationship of oak included here with fir and alder as a moisture indicator is discussed in Part IV.

The nonforest pollen shows several interesting phenomena. Maize pollen is abundant at upper horizons corresponding to archeological time, where there is also a high record of amaranths under which rubric are included chenopods. This group contains ruderals (plants of waste ground) and also species still cultivated in Mexico for their greens and edible seeds, and so indicates human activity. The group is again evident at lower levels, where the sediments record volcanic and tectonic activity. Teosinte and Tripsacum, close rela-

tives of maize, appear sporadically, and maize occurs as early as the 70-m level. Pollen of sedge, willow, and cypress is equivocal, indicating swampy conditions probably resulting either from the wet margins left by lake lowering or from a slow rise of the water table. Composites and grasses are a normal part of the valley flora. Many insect-pollinated species have left little or no record in the sediments.

Microfossils counted include pollen of woody and herbaceous seed plants and spores from ferns and mosses. Results are shown in Tables 1 (Madero) and 2 (Bellas Artes), along with a diagrammatic summary of Foreman's study of sediments. The groups identified are as follows:

Forest Pollen (AP)	*Nonforest Pollen* (NAP)
Pinus—pine	*Salix*—willow
Abies—fir	*Ilex*—holly
Picea—spruce	*Gramineae*—grass (small grains)
Quercus—oak	*Compositae*—composites
Alnus—alder	*Amaranthaceae*—amaranths and chenopods
	Spores—mostly ferns and mosses
	Higher Aquatics—sedges and cattails
	Unidentified—mostly herbaceous plants
	Taxodium—cypress
	Maydeae—mostly maize

Cypress pollen was not recognized as such when the Madero core was analyzed, but was recorded as an unknown in terms of relative abundance. Later, in the Bellas Artes core, identification was established from herbarium specimens (*Taxodium mucronatum*) collected in Mexico. Unfortunately, the original Madero slides were mounted in glycerine instead of the more permanent medium, glycerine jelly, and were discarded after counting. In general, however, cypress pollen recorded as occasional amounts to less than 10, as moderate 10–50, and as abundant over 50 per hundred AP.

Grass pollen grains over 75 microns (maximum diameter) are included under the column headed Maydeae, and although the grains were usually 100 or more microns in diameter, some teosinte and Tripsacum is represented. Maize identification at 70 m has been confirmed by Barghoorn *et al.* (1954, p. 238).

Foreman has tabulated other components in order of comparative abundance in the sediments. High pollen density is associated with the weathered sediments, and low pollen density with sands and fresh ash. The one exception is the archeological horizon between 3 and 6 m. Here forest pollen density is low in weathered sediments and may reflect either destruction of the native vegetation of the uplands and/or agricultural practices in the lowlands.

Correlation

The sites here studied are topped by about 3 m of unsorted fill and were emersed, as a part of the Tenochtitlan area, during much of archeological time.

Three properties of the sediments from the two cores have been selected as significant for correlation: (1) water content of the sediments (Zeevaert, 1953a, p. 301), (2) degree of weathering observed in the minerals (Foreman, 1955, p. 502), (3) pollen as indicative of climate.

WATER CONTENT: Surface subsidence in Mexico City has introduced serious foundation engineering problems. A subsoil profile for the city has been compiled by Professor Zeevaert (1954a, p. 301) from data acquired from measurements of water content, consistency and compressibility of the sediments to a depth of 80 m. The water content is significant only in fresh specimens secured below the water table, and is largely an index of particle size and the amount of clay present. Professor Zeevaert's figures of water content show a direct correlation with pollen density, Plate 2.

WEATHERING OF MINERALS: Professor Foreman divides the sediments into two main groups of materials: allogenic material composed of porphyritic ash and sand, and authigenic material formed by chemical precipitates and organic remains. The ash can be designated as "fresh ash", "weathered ash" and "clay", depending upon the degree of weathering as determined by the amount of hydration, aggregate polarization, iron-stain effect, and by the precipitated silicate material

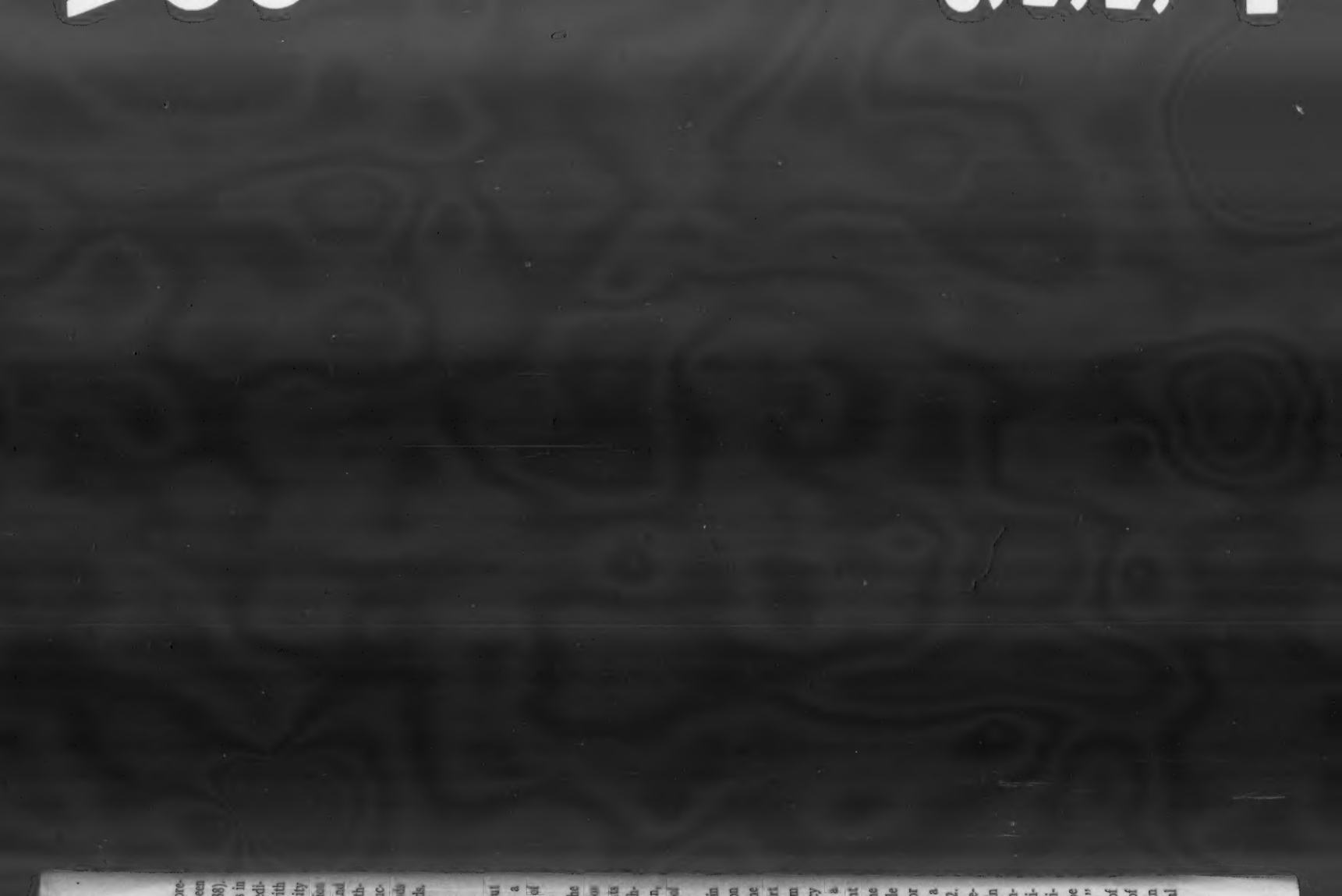
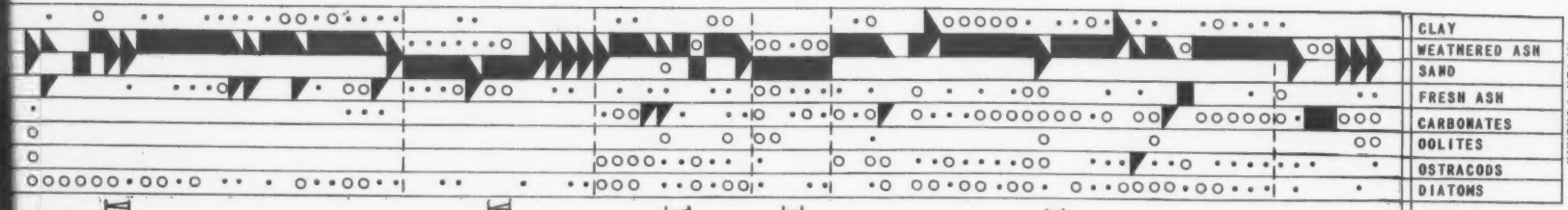
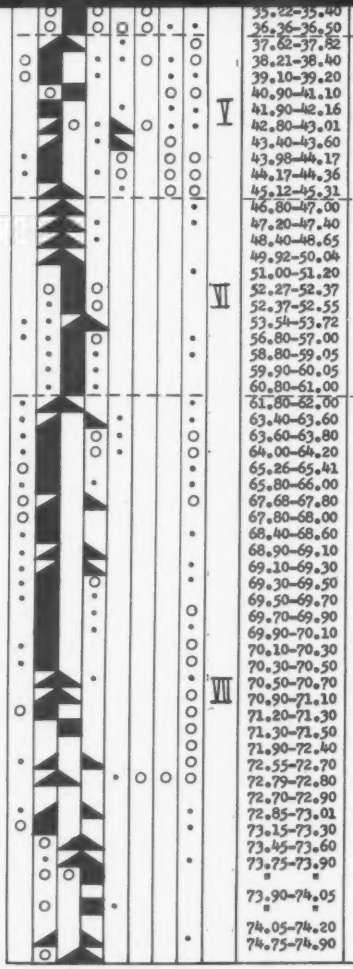


TABLE 2. POLLEN ANALYSIS OF BELLAS CORE



DEPTH - Meters	FOREST POLLEN DENSITY	FOREST POLLEN COUNT	PINUS	ABIES	PICEA	QUERCUS	ALNUS	OTHERS	NON-FOREST POLLEN DENSITY	NON-FOREST POLLEN COUNT	SALIX	ILEX	GRAMINEAE	COMPOSITAE	AMARANTHACEAE	SPORES	HIGHER AQUATICS	UNIDENTIFIED	TAXODIUM	MAYDEAE
3.60- 3.80	146	100	75	2		14	9		100	64	6		7	6	6	12	7	12	8	
4.40- 4.60	104	100	81	2		13	4		175	92	2		20	9	25	10	6	7	15	
5.10- 5.20	190	100	97	3		10	1		10	10			13	13	19	5	3	7	126	
5.70- 5.90	7	100	86	1		2	2		14	14								10		
6.10	104	100	94	1		4	1		1	1									1	
7.40- 7.60	59	100	95	2															136	
8.60- 8.80	656	100	84	3		7	1		90	5	1		1	2	1	2		2		
9.40- 9.60	1840	100	81	3		10	4		280	8			2	1	3	1				
9.60- 9.80	3040	100	97	1		2	6		100	3					1					1
10.00-10.20	3100	100	85	2		8	1		130	4					4	2				
11.00-11.20	3080	100	91	2		5	2		50	10					1					
12.80-13.00	1652	100	82	1		11	6		184	6										
"	2300	100	72	1		10	11		440	17	1	1	4	5	3	1				
"	3080	100	93	1		16	2		35	4	1	1	1	1	2					
13.02-13.20	1540	100	69	2		9	1		150	3			3	1	1					
14.10-14.60	835	100	94	1		2	1		62	3										
15.80-16.00	4600	100	85	1		11	3		645	20			15	2	1	2				
16.60-16.80	2320	100	91	2		12	1		135	6			4	1	1					
17.60-17.80	3045	100	91	1		7	3		0	0										
18.20-18.40	1840	100	94	1		7	1		100	5			3	2						
19.80-20.00	1540	100	95	2		3	1		210	16			2	1						
20.40-20.60	1530	100	94	1		3	1		170	6			7	3						
21.60-21.80	2350	100	91	3		3	1		0	0										
21.80-22.00	3080	100	91	1		5	2		615	19	1		9	2						
22.40-22.60	2300	100	85	1		6	1		130	4			2	1						
22.80-23.00	3060	100	99	1		6	1		80	3			6	2						
23.00-23.20	3050	100	90	2		7	1		162	10			4	1						
24.00-24.20	2300	100	91	1		6	1		37	4			4	2						
25.20-25.40	1840	100	89	1		9	2		92	6			5	1						
26.20-26.40	919	100	88	2		6	1		105	3			1	1						
27.80-28.00	2968	100	90	2		6	1		100	6			5	1						
28.60-28.80	1840	100	96	1		2	1		340	10			7	2						
29.20-29.40	3060	100	94	1		3	2		100	7			5	1						
30.40-30.60	3030	100	96	1		2	1		12	2			2	1						
31.00-31.20	1540	100	96	1		2	1		0	0										
32.12-32.30	42	42	26	1		12	3		0	0										
33.75-33.90	26	26	20	1		4	1		0	0										
34.10-34.20	0	0	0			0	0		0	0										
35.22-35.40	113	100	99	1		1	0		0	0										
36.35-36.50	0	0	0			0	0		245	1			1	1					1	
37.82-37.82	2310	100	86	1		10	3		0	0										
38.21-38.40	3080	100	88	1		7	5		20	2			1	2						
39.10-39.20	2300	100	91	1		7	2		46	4			2	1						
40.90-41.10	566	100	83	1		14	2		44	2			3	1						
41.90-42.10	1540	100	94	1		12	3		122	8			2	1						
42.80-43.01	1508	100	97	1		3	2		61	4			5	1						
43.40-43.60	1473	100	93	2		13	4		180	13			7	1						
43.98-44.17	1550	100	90	1		15	3		195	11			4	1						
44.17-44.35	1850	100	81	2		16	2		270	20			5	2						
45.12-45.31	1490	100	76	2		18	4		0	0										2
46.80-47.00	14	100	14						0	0										
47.20-47.40	0	0	0						0	0										
48.40-48.65	10	100	10						0	0										
49.92-50.04	1	100	1						0	0										
51.00-51.20	2	100	2						0	0										
52.27-52.37	200	100	87	3		7	3		0	0										
52.37-52.55	4	100	4						0	0										
53.54-53.72	0	0	0						0	0										
56.80-57.00	64	100	64						0	0										
58.80-59.05	6	100	61	5		3	2		0	0										
59.90-60.05	29	100	25	2		3	1		0	0										
60.80-61.00	37	100	86	1		7	2		0	0										
61.80-62.00	1150	100	91	1		5	2		0	0										
63.60-63.80	750	100	88	1		5	1		0	0										
64.00-64.20	1830	100	93	1		4	1		0	0										
65.85-66.01	580	100	94	1		4	1		0	0										
65.80-66.00	3080	100	87	1		8	1		0	0										
67.68-67.80	1530	100	87	1		8	1		0	0										
67.80-68.00	2960	100	94	1		4	1		0	0										
68.40-68.60	2300	100	88	1		6	2		0	0										
68.90-69.10	3100	100	81	2		8	2		0	0										
69.10-69.30	3080	100	94	1		3	1		0	0										
69.30-69.50	2300	100	88	1		6	2		0	0										
69.50-69.70	2320	100	94	1		4	1		0	0										
69.70-69.90	2310	100	96	1		3	1		0	0										
69.90-70.10	4700	100	96	1		3	1		0	0										
70.10-70.30	2300	100	96	1		3	1		0	0										
70.30-70.50	1840	100	96	1		3	1		0	0										
70.50-70.70	1540	100	96	1		3	1		0	0										
70.90-71.10	1040	100	96	1		3	1		0	0										
71.20-71.30	1540	100	96	1		3	1		0	0										
71.30-71.50	143	100	96	1		3	1		0	0										
71.90-72.40	655	100	96	1		3	1		0	0										
72.55-72.70	1150	100	96	1		3	1		0	0										
72.75-72.80	1550	100	96	1		3	1		0	0										


35.22-35.40
36.36-36.50
37.62-37.82
38.21-38.40
39.10-39.20
40.90-41.10
41.90-42.16
42.80-43.01
43.40-43.60
43.98-44.17
44.17-44.36
45.12-45.31
46.80-47.00
47.20-47.40
48.40-48.65
49.92-50.04
51.00-51.20
52.27-52.37
52.37-52.55
53.54-53.72
56.80-57.00
58.80-59.05
59.90-60.05
60.80-61.00
61.80-62.00
63.40-63.60
63.60-63.80
64.00-64.20
65.26-65.41
65.80-66.00
67.68-67.80
67.80-68.00
68.40-68.60
68.90-69.10
69.10-69.30
69.30-69.50
69.50-69.70
69.70-69.90
69.90-70.10
70.10-70.30
70.30-70.50
70.50-70.70
70.90-71.10
71.20-71.30
71.30-71.50
71.90-72.40
72.55-72.70
72.79-72.80
72.70-72.90
72.85-73.01
73.15-73.30
73.45-73.60
73.75-73.90
73.90-74.05
74.05-74.20
74.75-74.90
V
VI
VII
Dominant.
Two elements make up greater part of sediment.

35.22-35.40	115	100	99			1				9	8			8								
36.36-36.50	0	0								0	0											
37.82-37.82	2310	100	86	1		10	3			245	1			1						1		
38.21-38.40	3080	100	88			7	5			20	1			1								
39.10-39.20	2300	100	91			7	2			40	2			2								
40.90-41.10	566	100	83		1	14	2			46	4			3	1							
41.90-42.16	1540	100	82	1	2	12	3			40	2			2						1		
42.80-43.01	1508	100	97			3				122	8			5			3			31		
43.40-43.60	1473	100	83			13	4			61	4			3	1					27		
43.98-44.17	1550	100	80	1	1	15	3			180	13			7	4	2						
44.17-44.36	1850	100	81	1	2X	16	2			195	11			5	1	5						
45.12-45.31	1540	100	76	2	1X	18	4			270	20			11		7						2X
46.80-47.00	14	14	14							0	0											
47.20-47.40	0	0								0	0											
48.40-48.65	10	10	10							0	0											
49.92-50.04	1	1	1							0	0											
51.00-51.20	2	2	2							0	0											
52.27-52.37	200	100	87	3		7	3			12	5	1		2				2				
52.37-52.55	4	4	4							0	0											
53.54-53.72	0	0								0	0											
56.80-57.00	64	64	61			3				6	6			5		1						
58.80-59.05	6	6	5			1				1	1			1								
59.90-60.05	29	29	25			2	2			4	4			4								
60.80-61.00	37	37	35	1			1			17	17			17								
61.80-62.00	1130	100	91	1		5	3			23	2			2								
63.40-63.60	750	100	94			5	1			45	4			1	2	1						
63.60-63.80	1530	100	88	1		11				80	5			2	3							
64.00-64.20	1830	100	93	4		2	1			0	0											
65.26-65.41	1830	100	84			8	8			80	4			1	2			1				
65.80-66.00	320	100	87	1		12				40	12			2	1		9					
67.68-67.80	3080	100	89	1		6	4			243	8			4	2	1		1				
67.80-68.00	1530	100	73			13	14			140	9			3	4		2					
68.40-68.60	2960	100	87	3		8	2			100	3				3							
68.90-69.10	2300	100	94	1		3	2			70	3			1	2							
69.10-69.30	3100	100	81	2		9	8			310	11		2		5	1	2	1				
69.30-69.50	3080	100	88		1X	9	3			80	3			1		2						1X
69.50-69.70	2300	100	94			4	2			190	8			1	4	3						
69.70-69.90	2320	100	69	7		18	6			310	16			4	2	8						2X
69.90-70.10	2310	100	90			8	2			60	3			1		2						
70.10-70.30	4700	100	86	1		8	5			120	2				1	1						
70.30-70.50	2300	100	90			7	3			4040	179		5	14	17	49	78	8	5			3X
70.50-70.70	1840	100	74	5		16	5			55	3								3			
70.90-71.10	1540	100	82	2		11	5			40	3			1		2						
71.20-71.30	1040	100	87	3		9	1			3420	338	1	2	9	13	167	128	8	10			
71.30-71.50	143	100	68	3		26	3			220	140	1		45	36	43	9		6			
71.90-72.40	655	100	77	3		11	9			29	4			2					2			
72.55-72.70	1150	100	86	2		7	5			655	57			5	13	8	20	8	3			
72.79-72.80	1550	100	79	1		11	9			2555	171		16	45	31	39	14	16	10			
72.70-72.90	459	100	87			11	2			331	72		3	5	18	16	16	7	7			
72.85-73.01	2290	100	79	1		17	3			2050	89		4	9	16	16	20	20	4			
73.15-73.30	42	42	32	2		4	4			82	82		2	6	24	44	6					
73.45-73.60	0	0								1	1			1								
73.75-73.90	2	2	2							0	0											
" "	200	100	73			19	7	1		428	115	1	21	19	31	31			12			
73.90-74.05	210	100	77			13	6	4		128	61	3		11	10	13	11	8	5			
" "	4	4	2			2				0	0											
74.05-74.20	790	100	85	3		9	3			270	35			10	14	4	5					2
74.75-74.90	0	0								0	0											

X - Total pollen observed on one slide.

O Component important diagnostically but not great in amount.

nt. • Present but not important.

and the content of the clay mineral montmorillonite. The term "sand" is used for mineral grains ¼ mm–4 mm in size.

rence of spruce and cypress are also given. By combining the evidence in this way the climatic conditions associated with particular

TABLE 3.—STRATIGRAPHIC CORRELATION BY MEANS OF MECHANICAL CHARACTERISTICS AND PETROLOGY OF THE SEDIMENTS

Zeevaert			Foreman		
Depth (meters)	Zone	Water content	Depth (meters)	Zone	Dominant type of sediment
0–5.35 5.35–9	Arquielogico and Totoltzingo Caliche Barrilaco and Becerra	Low	3–8	2	Weathered ash, some sand and marl
9–33	Tacubaya	High	8–34	3	Weathered clayey ash
33–37	Tarango sand 1	Low	32–37	4	Ashy sand slightly weathered, few well weathered horizons
37–46	Tarango silt 1	High	37–47	5	Weathered clayey ash, some sandy beds in middle
46–61	Tarango sand 2	Low	46–62	6	Ashy sand and sandy ash, little weathering, poorly sorted
61–80	Tarango silt 2	Intermittent, low and high	61–75	7	Alternating fresh and weathered ash, some sandy layers

Authigenic materials are formed in the basin sediments through chemical precipitates of calcium and magnesium carbonates, clastic fragments of caliche (?), oolites, including tests of diatoms, ostracods, sponge spicules, carbonized plant fragments, algae, and pollen and spores.

Table 3 shows the zoning of the stratigraphic profile by Zeevaert and by Foreman, illustrating the close agreement of zone depth arrived at independently by the two investigators. The overlap of zone depths under Foreman is due to inclusion of both cores in the same column.

POLLEN AS INDICATIVE OF CLIMATE: The vertical distribution of climatically significant pollen from the upland forest is shown by means of cumulative histograms in relation to Foreman's sedimentary zones in Plate 1 (Madero) and (Bellas Artes). Data on the occur-

zones of sedimentation in the Cuenca can be surmised. Since the zones have been numbered from the top down, they will be discussed in chronological rather than numerical order.

Zone VII. The deeper Bellas Artes record (Pl. 1) begins with moist climate (producing much oak, alder, fir) during which there is evidence of extensive but intermittent volcanic activity.

Zone VI. This record is interrupted owing to extremely rapid deposition of sediments resulting from strong tectonic activity. However, in the few horizons of Bellas Artes (Pl. 1) where pollen counts could be made, generally moist conditions are indicated with possible subsequent drying. Madero (Pl. 1) shows initial moist conditions with a gradual, persistent shift toward drying at the close. This zone includes about 30 m of sediment.

Zone V. The turbulent episodes ceased and

were succeeded by a quiet stage in which 10 m of weathered lacustrine sediments collected. While the climate was not static, generally moist conditions prevailed.

Zone IV. Although Foreman describes Zone IV as one of intermittent tectonic activity with quiet intervening phases, the absence of fir and alder and scarcity of oak suggest an arid climate. Carbonates increase markedly in the middle beds of the zone, further suggesting dry conditions. It is therefore possible that the 3–5 m of sandy deposit was due to rapid upland erosion under conditions of diminished ground cover in a time of desiccation.

Zone III. These 25 m of weathered lacustrine sediments represent the longest stable sedimentary period within the 75 m studied. Although the pollen indicates alternating moist and drying climatic trends, the dry phases were evidently not severe enough to denude the landscape of vegetation, for there is no evidence of rapid deposition. The rate of sedimentation was fairly uniform throughout this time which is followed by an extremely dry period at the base of Zone II.

Zone II. Foreman suggests that this represents the warmest climatic stage. That it was dry for a short interval (2 m) in the beginning is indicated in Madero where oak, alder, and fir are completely replaced by pine, suggesting climatic conditions that existed during the dry Boreal of Europe and the pine period of the Mankato retreat in northern United States. Sand and marls are correlative with this dry interval and are overlain by weathered sediments in which abundant maize pollen reflects a rich agricultural economy, and pollen of oak, alder, and fir are again increased. The horizon between 4 and 5 m contains a profusion of artifacts from the Nahua culture which began about 900 A.D.

Zone I. This consists of fill.

Spruce and cypress pollen grains are auxiliary indicators. The former appears only in Zones III, V, and VII where it may reflect cooler temperatures than the moist upper interval of Zone II. The youngest cypress swamp is missing in Madero because of a gap in the samples, but earlier swamps are evident in Zones III and V of both cores. The presence of cypress in these zones of weathered sediments substantiates Foreman's conclusion that the water levels were never very high in this area of the Cuenca, even during moist climatic intervals. The absence of cypress below 44 m may reflect either deeper water or a change in chemical habitat, for these sediments are extremely low in carbonates and ostracods. Cypress is known to grow in habitats with a calcareous substratum, and Davis (1943, p. 179) emphasizes the initial importance of occasional low water to permit aeration of growing seedlings.

Pollen Density

Early workers in pollen analysis often recorded pollen frequency as the number of pollen grains per unit of slide surface. Partly because this only approximated abundance and partly because without sedimentary studies it gave little essential information, the practice was largely abandoned. However, for the present prolonged sedimentary record involving much geological and climatic change, pollen density is diagnostically significant.

The figure used to designate density is the number of grains either counted on or calculated for 1760 sq. mm of slide surface. Since larger samples of sediment were used in horizons containing little pollen, the spread or amplitude of figures for pollen density is compressed, the low values being recorded in exaggerated proportion as compared with the samples in which pollen was abundant.

During periods of slow and uniform deposition of finely colloidal material (monmorillonite clay with high water-holding capacity), forest pollen density is high. Zone III, for example, contains evidence of climatic fluctuations, but neither the dry climatic swings nor physiographic changes destroyed enough of the vegetation to reduce pollen output or leave the soil exposed to erosion.

Recurring stages of low pollen density are marked by sediments, low in water-holding capacity, whose physical and chemical condition indicates rapid deposition with consequent dilution or maceration of pollen. The causal factors, whether climatic, tectonic, volcanic, or biotic, of such rapid sedimentation must be considered in the light of all available evidence in each horizon where such conditions occur.

Plate 2 shows the remarkable agreement in the patterns formed by water content, weather-

ing of the minerals, and pollen density. The correlation of patterns formed by Zeevaert's figures and pollen densities is not accidental, but reflects natural phenomena.

TABLE 4.—MEDIAN POLLEN DENSITY BY ZONES

Foreman	Forest Pollen		Nonforest Pollen		Remarks
Zone	Madero	Bellas Artes	Madero	Bellas Artes	
IIa	218	146	268	100	Agriculture
IIb	9	15	0	2	
IIc	263	656	3	0	Xerothermic
III	1840	2300	125	103	Weathered
IV	42	26	3	2	Sand
V	1160	1550	170	91	Weathered
VI	3	6	1	0	
	2073†		4900†		Tectonic
VII		2300		140	Intermittent
		180*		15*	Volcanic

* Volcanic activity.

† Quiescent phase.

Note: Tables 4 and 5 are based on suggestions of Professor Wade Ellis of Oberlin and were calculated by him.

A convenient means of discussing pollen density was suggested by Professor Wade Ellis of Oberlin and is used in Table 4 where zones II through VII are listed along with the median pollen density figures. These medians are of use as the measure of central tendency in any of the specified stratigraphic zones and serve as a basis of comparison between zones. Median figures from Zone III, because of its general uniformity, are considered the best standard of comparison. Marked deviation from the high forest and low nonforest median densities in this zone indicate, for either core, climatic and/or sedimentary changes.

Plate 2 and Tables 1, 2, and 4 show clearly that Zones II, IV, and VI are marked by extremely low median densities. Zone II starts with arid conditions which may have reduced ground cover and promoted erosion; the succeeding moist phase was accompanied by intensive agriculture. Zone IV is arid, but Zone VI is a time of strong tectonic activity resulting in rapid deposition with pollen dilution and/or maceration thus explaining the low median density. Two brief intervals in Zone VI of Madero, however, are quiescent sedimentary phases marked by high median densities for both forest (2073) and nonforest (4900) pollen. The extremely high nonforest median of 4900

TABLE 5.—MEDIAN POLLEN DENSITIES, ZONE VII (BELLAS ARTES)

Meters	Forest	Nonforest
61.80–62.00	1150	25
63.40–63.60*	750	45
63.60–65.40	1830	80
65.80–66.00*	320	40
67.68–71.30	2300	165
71.30–73.40*	399	125
72.55–72.80	1350	1605
72.70–72.90*	459	331
72.85–73.01	2290	2050
73.15–74.90	43	1

* Volcanic activity

shows the mass invasion of ruderals following surface disturbance.

Zones III and V represent stable periods with slow accumulation of sediments and high-median forest pollen density (2300 and 1550). Zone VII, on the other hand, when broken down as in Table 5, shows the unmistakable association of high forest pollen density with weathered ash, and low density with fresh ash. The high frequency of nonforest pollen following ash deposition indicates the same type of ruderal response to volcanic wasteland as that following tectonic activity. Apparently the ash falls above 64 m were less severe in areal extent than the earlier ash falls in the zone.

One of the significant facts brought out by pollen density is that the increase in nonforest pollen is never at the expense of forest pollen but rather a reflection of disturbed surface conditions, whether accelerated by nature or man.

Increased abundance of amaranths and chenopods, although a reflection of disturbed surface areas, is evident in moist climatic stages whereas current valley flora is dominated by semiarid genera such as agave and cacti.

CONCLUSIONS

Basin sediments through the 75 m analyzed contain pollen from the surrounding uplands,

pollen dominated by pine, oak, alder, and fir with a few spruce. These genera, with the exception of spruce, have persisted to the present, indicating no extreme climatic changes during the time interval involved in this study such as occurred in continental glaciated areas where subarctic flora was replaced by moist temperate flora. Changes occurring in the percentage composition of the forest reflect changes in available moisture and thus of climate, while changes in density of recoverable pollen reflect changes in rate of deposition and weathering of the sediments.

The present valley flora is largely composed of semiarid insect-pollinated plants, but in the past grasses, composite, and amaranths grew during relatively moist stages which were preceded by surface disturbance. Cypress swamps are evident at recurrent intervals above 45 m.

Correlation of the sedimentary components distinguishes climatic change from volcanic and tectonic activity, thereby recording conditions within the area at times influenced by climate and at others controlled by geological events.

The following climatic interpretations are based on the work done by Dr. Zeevaert and Dr. Foreman in correlation with the pollen.

Zone VII: Active volcanism interspersed with quiescent phases; climate moist with short interval drying stages

Zone VI: Strong tectonic activity; climate moist

Zone V: Weathered sediments, stable lacustrine stage; climate relatively moist with short interval drying stages

Zone IV: Rapid deposition; climate drying

Zone III: Weathered sediments, stable lacustrine stage; climate relatively moist with drying phases

Zone II: Weathered sediments following sands and marls; climate dry to moist

Interpretation of temperature changes will be presented in Part IV.

Studies now in progress on deep cores from New Mexico support the conclusions arrived at in the present work concerning Wisconsin climate, and further suggest that the Mexican cores do not penetrate an interglacial period.

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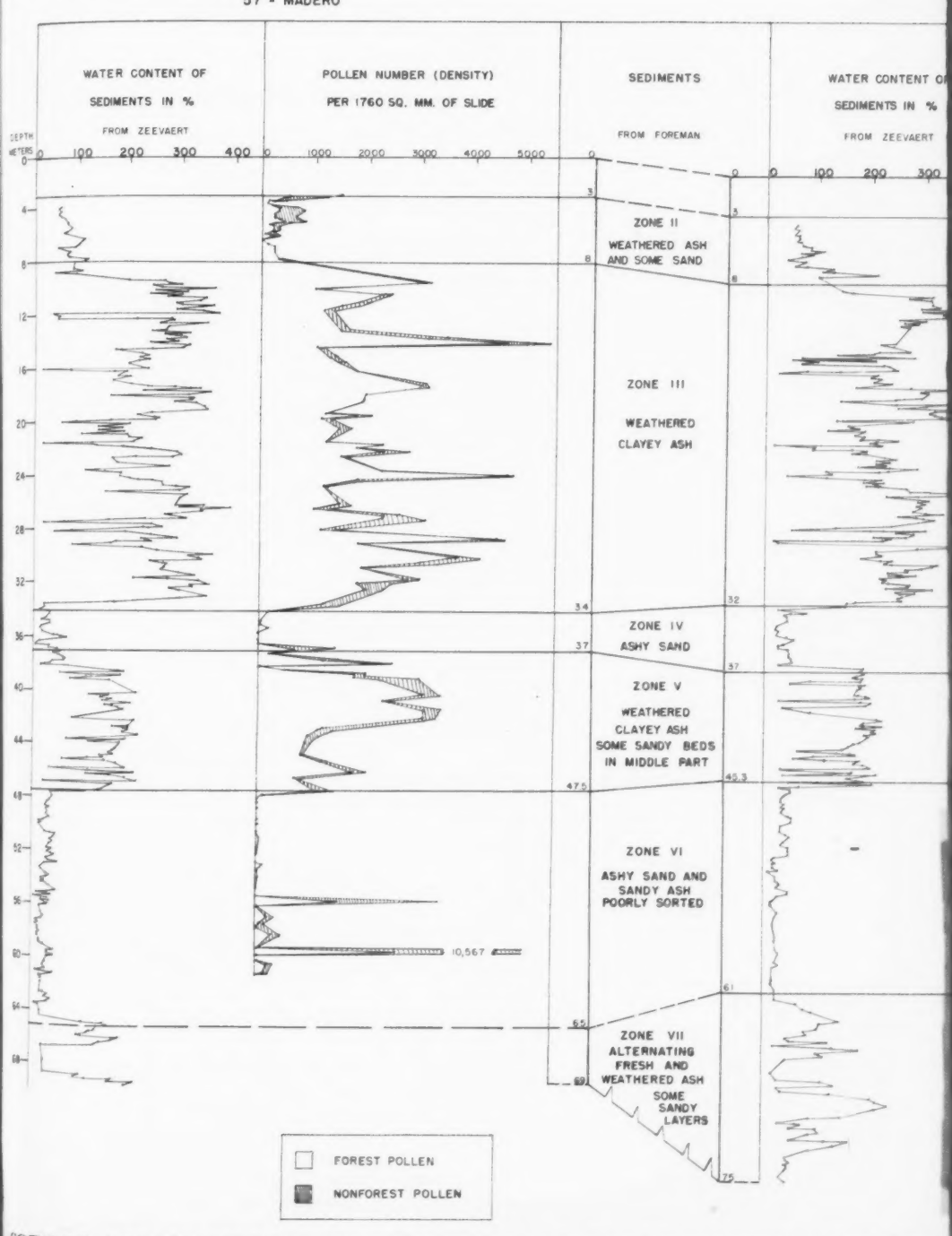

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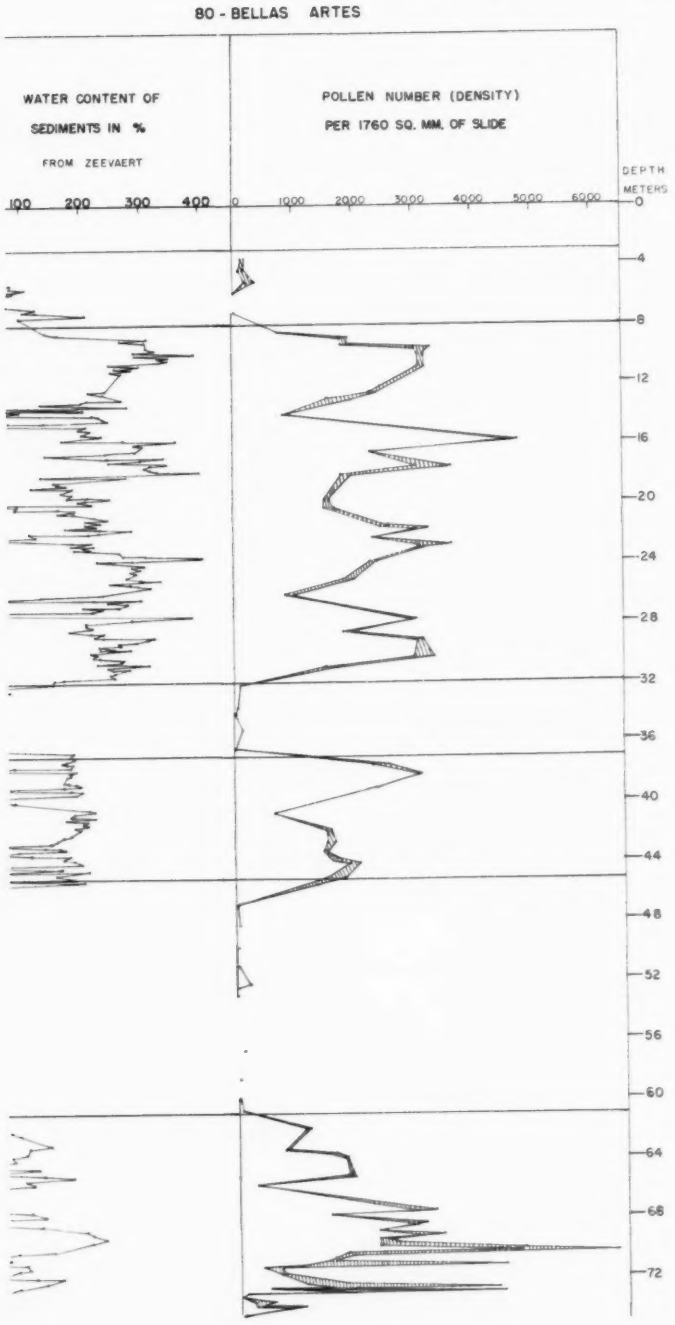

. AND WEATHERING OF THE MINERALS

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VOL. 66, PP. 521-530, 6 FIGS., 1 PL. MAY 1955

PALYNOLOGY IN SOUTHERN NORTH AMERICA

PART IV: PLEISTOCENE CLIMATE IN MEXICO

BY PAUL B. SEARS AND KATHRYN H. CLISBY

ABSTRACT

Pollen analysis of two deep lacustrine cores under Mexico City indicates a series of moist-dry oscillations with longer trends of changing temperature—a climatic record which appears to extend as far back as early Wisconsin. The individual moist pulsations, although marked by warmth, were evidently times of glacial nourishment; the dry phases, some of which were cool, were evidently times of abatement.

The upper 50 m of the profiles indicate two episodes of maximum glaciation; the details that follow the more recent agree with present knowledge of the Cary-Mankato-Latest sequence of the Wisconsin. Under milder conditions between the postulated Tazewell and Cary glacial maxima, soil might have formed on exposed till. The base of the profiles indicates warm-moist conditions with falling temperature to about 50 m. Because of tectonic and volcanic disturbance, it is not clear whether this cooling represents a separate advance or merely an early phase of the first maximum above the 50-m level.

For the tropical Mexico City area, it is shown that the moist periods of glacial nourishment were also relatively warm.

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OBJECTIVE

The basic purpose of this study is to extend and refine knowledge of Pleistocene climate; for this a sedimentary record from Mexico City was used. Microfossils, especially those representing the sequence of upland forests, are correlated with the discontinuous evidence of the Pleistocene available within the limits of continental glaciation.

This sedimentary record has been presented and evaluated in the three preceding papers. It reveals a long succession of climatic pulsations of sufficient intensity and duration to affect dominant vegetation. In view of the present warm-dry trend in progress since 1750, accompanied by the increasing demands of modern civilization for available water, these results together with similar studies now under way

may carry practical implications not at first contemplated.

Pollen Record as an Index of Climates

The record in the Cuenca de Mexico, as at Lake Patzcuaro (Deevey, 1944, p. 144), is formed by the interplay of four pollen genera: fir (*Abies*), alder (*Alnus*), oak (*Quercus*), and pine (*Pinus*), (Sears, 1952, p. 244). These four genera largely compose the present upland forest, a zone ranging from about 2300 m to timberline at 3800 m. Below this forest belt the Cuenca is bordered by scrub, desert, and grassland. It is especially arid toward the northern margin. Grassland extends downward into the valley floor, save where local moisture permits the growth of tule marshes (reed and rush) or of edaphically controlled trees such as willow (*Salix*) and cypress (*Taxodium*). Cypress pollen, together with nonforest pollen, has been tallied as so many per hundred of the forest pollen, and not included in the main percentage calculations.

The upland forest pollen reveals most clearly any major climatic change; the others are often of great supplemental value as indicators of more local changes. Thus the nonforest pollen, such as that of composites (*Compositae*), amaranths (*Amaranthaceae*, *Chenopodiaceae*), and grasses (*Gramineae*), shows brief but sharp increases following disturbance by volcanic, erosional, or human activity, while the maxima of marsh and swamp pollen may be associated with low-water stages.

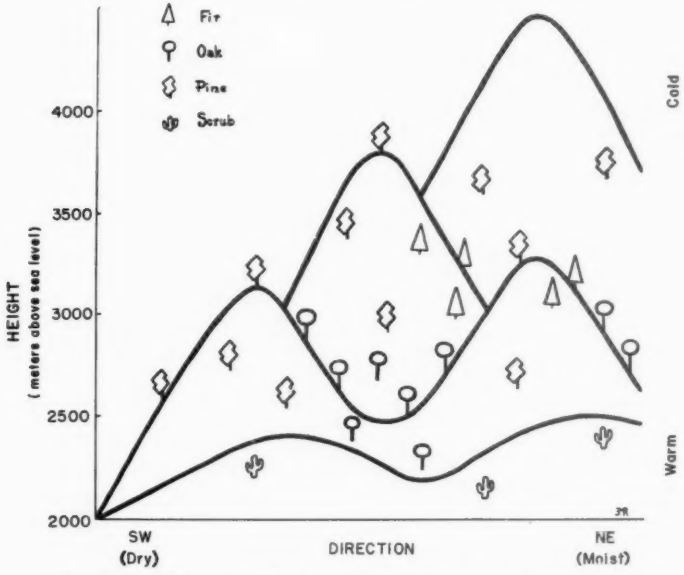
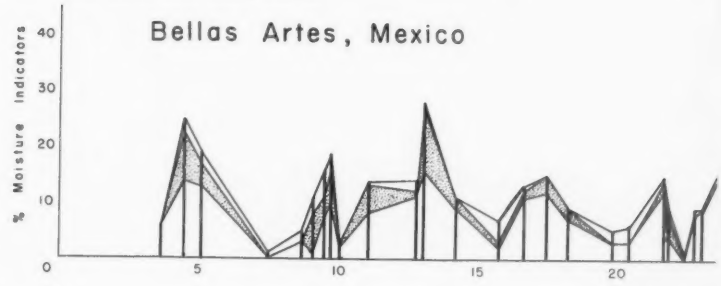
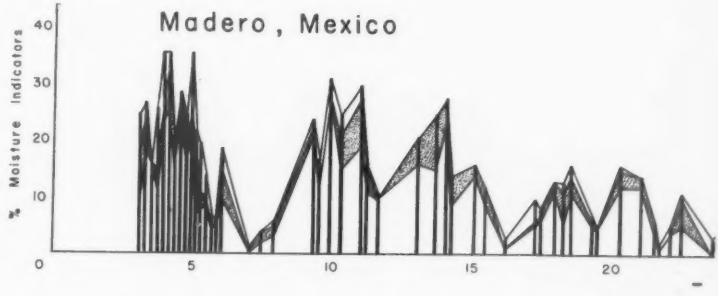


Figure 1.—Ecological Distribution of Upland Forest Genera
Fir on moist sheltered slopes—3000–3500 m—oak in moist ravines 2300–3000 m—pine on ridges, dry exposed slopes and at elevations above 3500 m; alder of moist habitats not shown; oak, confined to low elevations, indicates warmth as well as moisture.

The writers know of no studies of the temperature and moisture limits of the upland forest species and so judge their indicator value by the most general altitudinal and ecological observations. (*Cf.* Martinez, 1945.) Revision of previous notions of vertical distribution of the pines (Sears, 1952, p. 244) is now possible. However, pine is still considered a dry indicator in comparison with oak, alder, and fir.

The various species of oak differ somewhat in ecology, and are not at present distinguishable by their pollen. This holds true for pine, also. However, the broad pattern of the upland





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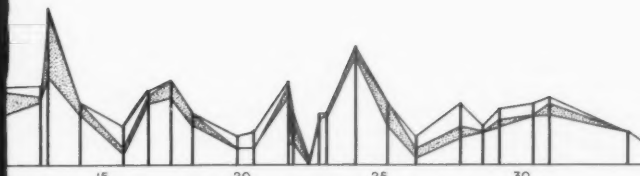

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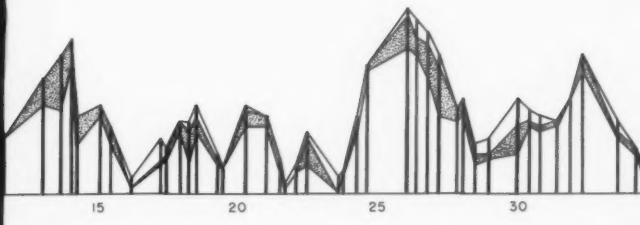
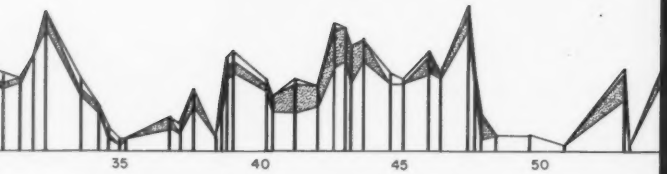


CUMULATIVE BAR GRAPHS OF MOIST I

Bars show location of samples analyzed. Alder stipp



OIST INDICATORS IN BELLAS ARTES AN
lder stippled, separating oak below from fir above. Drawing by

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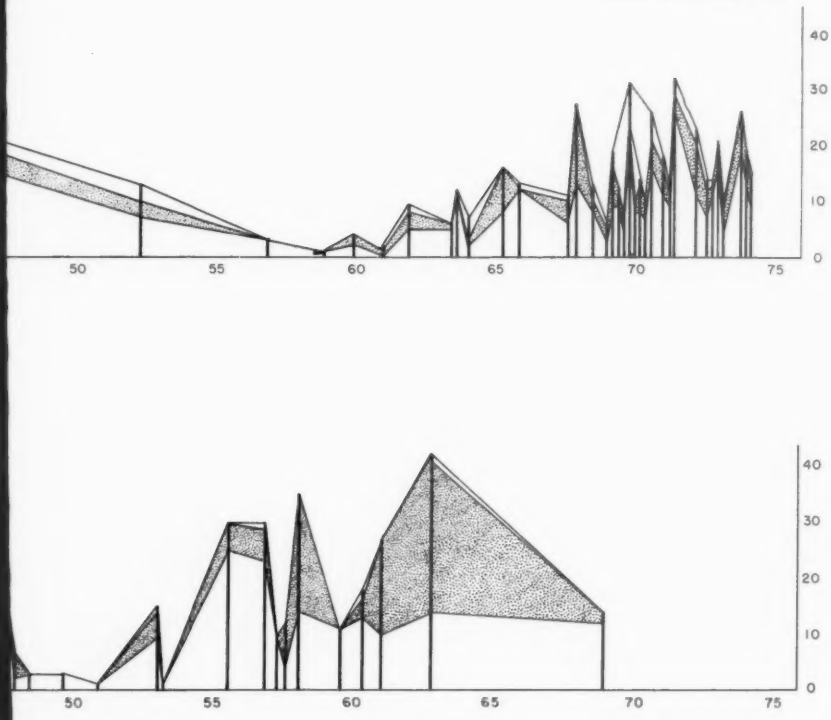

S ARTES AND MADERO CORES

ove. Drawing by Edith M. Reed.

forest is clear. The pines range from timberline at 3800 m down almost to the lower forest limits. At 3500—3000 m there is fir, but it is confined to the moist slopes, while pine grows on the dry slopes and on ridges. From about 3000 m down oak and alder occupy moister sites than pine, oak growing in the ravines, alder beneath the forest canopy, and pine on the ridges (Fig. 1).

Pines vary in moisture requirements, *P. patula* approaching oak in mesophytism, but their selection of habitat when at the same altitude shows that oak indicates the moister, as well as warmer conditions.

In the Valley of Mexico as in southwestern United States oak forms a xerophytic forest below the pine zone at the upper margin of the dry scrub or grassland. Here, however, oak is favored against scrub and grass by increasing moisture as it is at higher altitudes against pine. Plate 1 shows that high oak counts are usually accompanied by alder, a definite moisture indicator. Intervals in which the three moist indicators are scarce and pine abundant are considered dry. Oak accompanied by high pine at such levels probably represents warmer conditions than where only fir is found with the pine. But a moderate increase of fir at moist levels (high oak plus alder) is a normal effect, at higher elevations, of such moisture increase.

In general oak and alder occupy the moist sites at lowest and warmest altitudes and indicate moisture and warmth. Pine, on the other hand, generally indicates dryness and slightly cooler conditions over a wide temperature range. Fir noted in the profiles is not abundant but is clearly an index of moist conditions at cooler elevations, being favored by the moisture that favors oak and by the coolness that favors pine. The sharp antithesis of oak and pine and the close relation of oak and alder are significant.

Although the various species of *Quercus* and *Alnus* cannot as yet be distinguished by their pollen and none of the four genera have received adequate ecological study, some general norms can give consistent and reasonable results. By these norms oak and alder may be proposed as indicators of warmth and moisture, and fir of coolness and moisture. Pine, whose abundance is in inverse proportion to the sum of these three, is considered as a measure of less moisture than they indicate, and of lower temperature than oak.

Completion of the Record

The sedimentary record at both Madero and Bellas Artes is truncated and incomplete, since these sites were long occupied by man. To continue this record to the present, recent profiles are needed to reconstruct the top levels of the two deep cores. The fortunate finding of an active peat bed surrounded by forest (Zempoala) gives current information and overlaps sufficiently with three other slightly truncated profiles for this purpose. These three are: Chapingo and Chimalhuacán (Sears, 1952, p. 251–253), Xico, obtained in 1948 by Arellano and analyzed shortly thereafter and Zempoala profile. An equilateral triangle with sides of about 22 km would have Bellas Artes and Madero at the western apex, Chapingo at another, east and slightly north, and Xico to the southeast at the third. Chimalhuacán lies within this triangle, at the apex of an isoceles triangle whose base is the 22 km separating Bellas Artes and Madero from Xico and whose equal sides are about 18 km in length (Fig. 2).

Rainfall is greatest at Xico, diminishing toward the north. Thus the profiles vary in local climate as well as position. Chapingo and Chimalhuacán cores were taken within the former border of Lake Texcoco, Xico from the old bed of Lake Chalco—all at sites drained by 1900 A.D., and subjected to an uncertain

Table 1.—Correlation between Pollen Percentages by Pairs of Upland Forest Genera

Relation	Coefficient (r)*		Significance
	Bellas Artes	Madero	
Pinus-Quercus	−.68	−.73	Inverse
Pinus-Alnus	−.76	−.60	Inverse
Pinus-Abies	−.27	−.11	Slight inverse
Abies-Quercus	+.09	+.17	Slight direct
Quercus-Alnus	+.32	+.35	Direct
Abies-Alnus	+.05	−.06	No correlation

* Calculated by Mr. Wallace Bowman.

amount of disturbance since. This made it advisable to find a site where pollen from fairly undisturbed forest is still being deposited.

Such a site was found in 1950 with the aid of Drs. Manuel Maldonado-Koerdell and Luis Aveleyra at Zempoala, about 50 km southwest

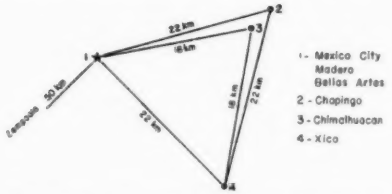

FIGURE 2.—LOCATION OF MEXICAN PROFILES STUDIED

of Mexico City, at an elevation of about 3000 m. Here active domed peat bogs occur in a basin surrounded by forest. (*See* frontispiece, Martinez, 1945.) Moist slopes are covered by fir, drier exposures by pine. Alder forms a mesophytic undergrowth, and oak is present at lower altitudes. Thus conditions are unusually favorable not only for producing pollen indicative of climatic changes, but also for preserving this pollen. The actual peat column is short—about 2.5 m—but it records three climatic episodes. From the top down these are: Dry (D), the present trend; Moist (M), shown by Sears (1952, p. 253) to have accompanied the rise of Nahua culture in the Cuenca; and Dry minus 1 (D-1), which rests upon gravel, indicating heavy erosion probably associated with a reduction of vegetative cover and appears to represent the very dry period around 500 B.C. at the transition from Late Archaic to Teotihuacan.

The upper 3 m of Madero and Bellas Artes consist of fill (*relleno*) below which artifacts (possibly intrusive) occur at depths of 4–5 m in the layer M-1. Since the layer D-1 at 1.3–3.4 in the shallower profiles has been shown to fall within ceramic time, there is stratigraphic support for the agreement of the curves (Fig. 3). The Zempoala curve is reduced to compensate for its more rapid sedimentation, while the curve for Xico has been omitted as the correlative zones are thicker.

A comparison of Figure 3 and Plate 1 shows how the shallow profiles complete the record of the deeper ones, thus making it possible to use the present as a starting point. Relative temperatures are not mentioned since the moisture fluctuations are sufficient to establish correlation.

CORRELATION WITH PLEISTOCENE HISTORY

Recurrent ice movement and intervals of weathering and erosion have obscured—frequently destroyed—many important expressions of glacial activity during the Pleistocene. Besides this, the wide extent of glaciation has resulted in disorganized terminology (Flint, 1947, p. 197).

TABLE 2.—CORRELATIVE CLIMATIC ZONES IN SHALLOW AND DEEP PROFILES
(in meters)

Climate	Zempoala	Xico	Chapingo	Chimalhuacán	Madero	Bellas Artes
D*	0	...	...	...	...	...
M	1	1.9	.2	.5	...	...
D-1	2.5	3.4	2.3	1.3	...	...
M-1	...	6.0	5.3	4.0	4.1	4.5
D-2	...	7.8	7.3	7.5	6.8	7.5
M-2	...	...	...	...	9.9	9.7
D-3	...	...	...	...	11.6	10.1
M-3†	...	...	...	...	14.0	13.1

* Present.
† Oldest.

Thus the sedimentary record of a Pleistocene basin not invaded by ice is of especial value as a source of continuous information from which a master sequence may be worked out. Given such a sequence, the discontinuous pieces of direct evidence may gradually be fitted into place, while episodes for which no direct evidence exists may be reconstructed with some assurance.

Imperfect as the records are, alternating moist and dry episodes are obvious. A larger pattern is found by smoothing the curve connecting the moist-warm maxima. (*See* Fig. 4.) Three sequences then become apparent above the 50-m level, as follows:

A. A gradient beginning at 50 m and falling to a minimum somewhere between 35 and 40 m

B. A second gradient rising from this minimum to the vicinity of the 25-m level, at which point there is an abrupt drop
C. A third gradient rising from about 23 m to the top of the profiles

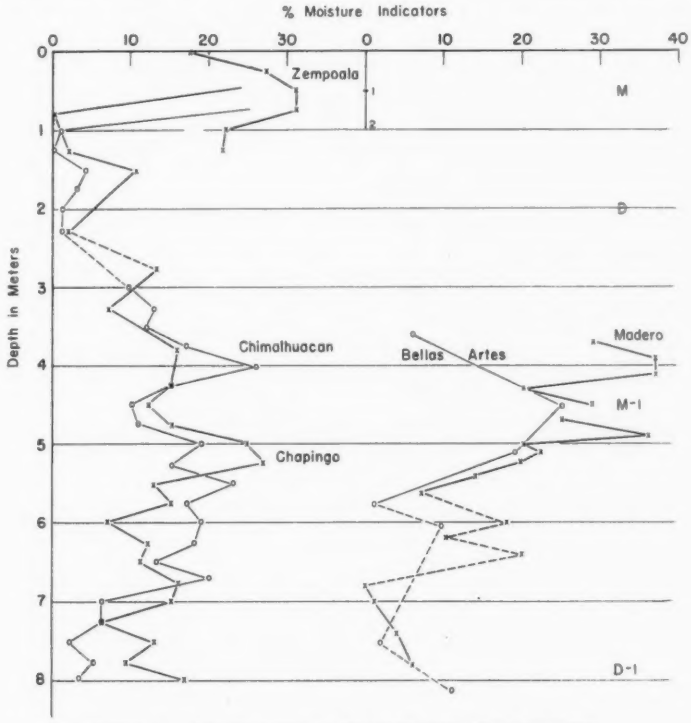

FIGURE 3.—CORRELATION OF SHALLOW AND DEEP PROFILES

To borrow a useful comparison from physics, each falling gradient resembles a series of damped oscillations, with increasing constraint upon the intensity of the included maxima. The rising gradient resembles a sequence of undamped or forced oscillations of increasing amplitude, shown by increasing height of the maxima. The troughs between crests have less to do with the gradients, for they cannot go below 0 per cent of moist indicators and frequently approach that limit.

Since the oscillations are based chiefly upon oak and alder, which indicate warmth as well as moisture, two environmental factors are involved. The gradients express trends of temperature, no less than moisture. In a rising gradient, therefore, the oscillations take place under conditions of rising temperature levels, while the falling gradients represent gradual cooling. The interplay may not necessarily operate with mathematical precision and regularity. If the gradients represented moisture trends only, the maximum aridity would be associated with high temperature, while the opposite is apparently the case. These data do not give sufficient information on temperature conditions during the dry intervals. But the high pine count is accompanied only by fir frequently enough to suggest that some of these arid periods, at least, were cool. The pattern may be generalized, then, as one of moist-dry oscillations under the control of temperature. If we were dealing with a series of temperature oscillations under the control of moisture, the phases would be reversed to cool-moist and warm-dry. Actually they are moist-warm and dry-uncertain.

It is assumed that moist intervals are necessary to glacial nourishment, wastage being due to aridity or warmth or both. The tops of the profiles of Figure 3 and Plate 1 support this assumption. The moist interval above 1 m and in northern United States, both by the pollen record and carbon dates (*Cf.* Deevey's C_1-C_2 5305 ± 250 *in* Johnson, 1951, p. 6).

The still earlier oscillations probably have a similar relation to glacial activity at higher

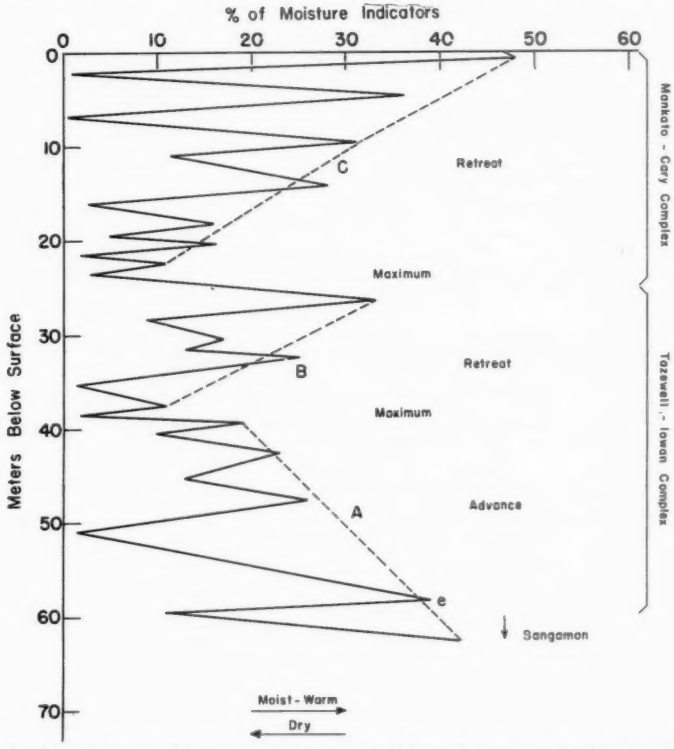

FIGURE 4.—SUCCESSION OF MAXIMA AND MINIMA OF MOIST INDICATORS IN MADERO PROFILE
Temperature gradients based on moist maxima

including the archeological date of 800–900 A.D. (Sears, 1952, p. 246) represents the latest (Alaskan and Norwegian) advance. The dry interval around 2 m and including the archeological and carbon date of about 500 B.C. falls between the ice-free time of forest growth in Alaska of 3500 ± 250 (Heusser, 1953, p. 637) and the dry oak-hickory (C2) date from Upper Linsley Pond of 2141 ± 250 (Johnson, 1951, p. 6).

The moist interval around 5 m includes a date of 4900 ± 250 (Suess, 1954, p. 472) and while ice movement during this time is still problematical, conditions were cool and moist latitudes and altitudes, ice nourishment taking place during the moist intervals and ceasing during the dry. The moist crests were also warm in these profiles since Mexico City lies between Lat. 19 and 20 N, well within the tropics and approximately 1000 m below the lowest moraine on Ixtaccihuatl, about 60 km distant. The suggestion that glaciation may be promoted by warm moist conditions within the tropics is not new, although direct evidence to that effect has been lacking. Commenting on this phenomenon, Professor H. C. Willett writes "at least from the point of view of this meteorologist, your paradox is not at all a paradox.

but quite the contrary." (Personal communication.) Although the cores extend to 69 and 75 m, the evidence below 50 m is fragmentary, owing

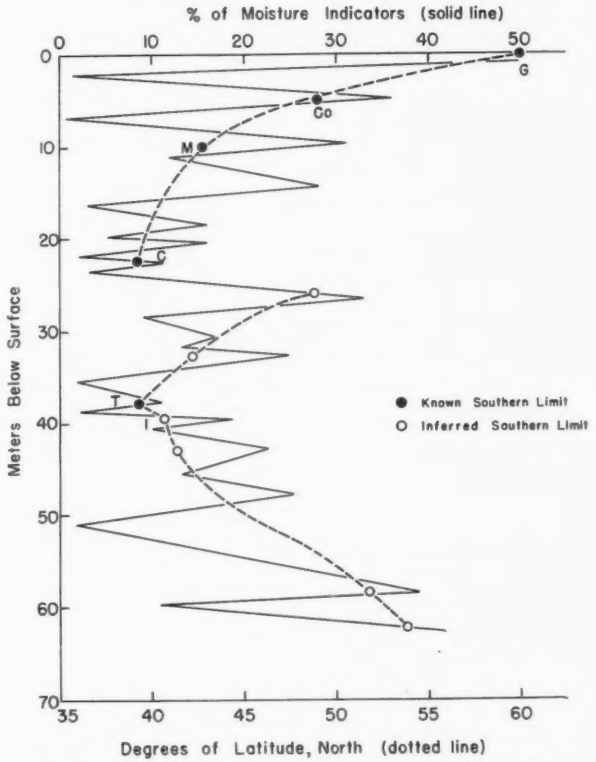

FIGURE 5.—VALUES OF MOIST MAXIMA, MADERO, IN RELATION TO KNOWN AND INFERRED POSITIONS OF THE WISCONSIN ICE FRONTS

largely to tectonic and volcanic activity. Both cores show evidence of high temperature and moisture at their lower levels, and Bellas Artes shows some indications of a falling gradient preceding gradient A. But in view of the rapid sedimentation of Foreman's (1955, p. 497) Zone VI, the time interval may have been short. The high values below 50 m could easily be early phases of gradient A.

In any event, gradient A seems to represent a series of interrupted glacial advances culminating in a maximum of some duration at around the 35–36 m level. Gradient B probably represents a considerable retreat, followed by an abrupt shift to another glacial maximum at 22–23 m in Bellas Artes, 23–24 m in Madero. From this point to the top the series of conditions in gradient C seem appropriate to a prolonged and vacillating retreat culminating in the present.

If these explanations are justified, the Mexico City core shows evidence of the two latest glacial maxima separated by a warmer interval which, while not free from glacial activity, must have cleared the ice from an extensive area.

Sears is of the opinion that gradient C represents the Cary-Mankato-Latest sequence, since the number of episodes recorded agrees fairly well with the number of advances and retreats postulated for that sequence. If this is true, gradient B may suggest the presence of a soil profile separating the Cary and Tazewell. Gradient A could represent the Tazewell ad-

vance or some early Wisconsin advance which remained fairly static during the prolonged dry interval around 36 m,[1] and which could be marked by loess formation. In the latter event the Tazewell would be represented by the initial cooler stages of gradient B.

Figure 5 has been derived by plotting moist (warm) maxima as to position and intensity (percentage of moist indicators). Known positions of the ice front are plotted in terms of N. latitude; the approximate longitude of Ohio is used except for the present ice in Greenland and Alaska. Since a relationship probably exists between intensity of the maxima and position of the ice front, when the latter is not known it can be inferred. In general, there was a gradual advance from Late Sangamon to the Iowan-Tazewell limits, a Tazewell retreat from those limits to a position comparable with that of the Latest minus 1 ("Cochrane"), a rapid readvance to Early Cary limits, and then a final sequence of retreat involving the Cary-Mankato-Latest series.

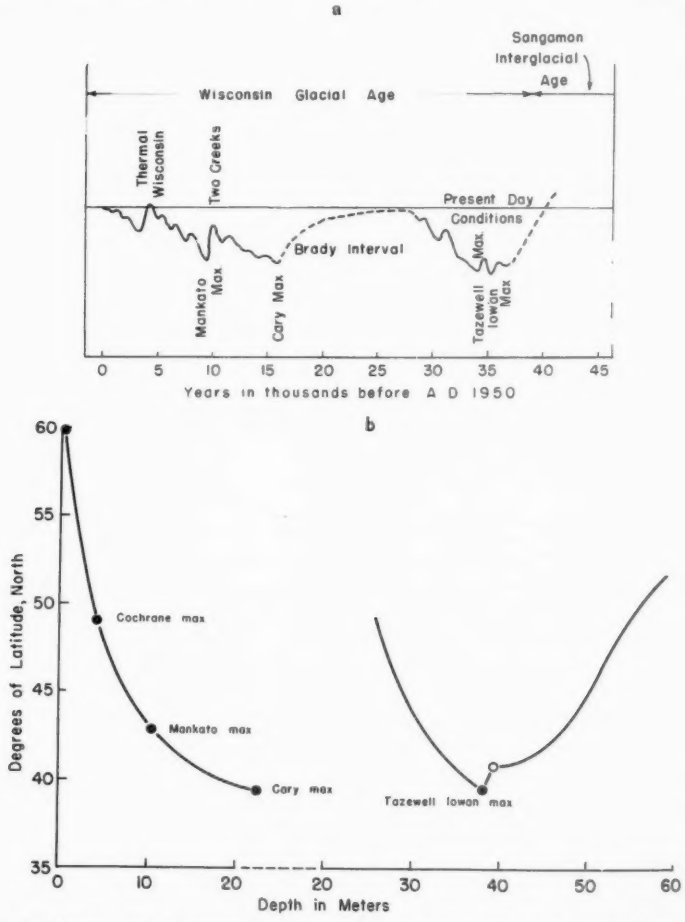

FIGURE 6.—KNOWN AND INFERRED POSITIONS OF THE WISCONSIN ICE FRONTS (B) COMPARED WITH FLINT'S RECONSTRUCTION OF WISCONSIN CLIMATES (A)

[1] *Cf.* a recent Carbon 14 date in excess of 32,000 for material from 33 m in the Tarango Sand 1. (*See* Foreman, 1955 and Zeevaert, 1952.)

The draft of this paper had been completed before examination of the "curve showing variations in climate during the Wisconsin age, mainly as inferred from glacial-geological data" as constructed by Flint (1953, p. 174). Conclusions presented here are thus an independent confirmation of his views. In addition, the Mexican profiles have a continuity and quantitative character not available in his evidence. We have not revised this paper, adding instead, with Professor Flint's kind permission, as Figure 6 a comparison of his climatic curve with ours. Further refinements may alter some of our interpretations, but for the present they give a reasonably consistent pattern.

Some important work, mostly in Mexico, discusses the late Wisconsin sequence—*cf.* gradient C. This includes the pioneer work of Bryan (1948) on the fossil soils and climatic changes in the Cuenca de Mexico, and that of Arellano (1951) on the upland stratigraphy, also the work of de Terra *et al.*, (1949) on Iztaccihuatl and of White (1951) on Popocatepetl, and of Moss and his associates (White, 1953) on the Eden Valley sequence.

De Terra, for instance, finds four marked ice advances on Iztaccihuatl—Salta at 3100 m, Xopana at 3200–3300, Trancas at 3400, Ayolotepito at 4350—and three sets of recessional moraines between 4350 and the present ice at 4600 m. White, using melt-terraces, finds evidence of five periods of Wisconsin glaciation on Popocatepetl. Since few of the glacial features at these high elevations could survive the tectonic activity recorded in Foreman's Zone VI (below 48 m) and the equivalent of the early Cary advance, and since some subsequent evidence has probably been lost, the agreement is reasonably good. So is agreement with the phases of the Eden Valley in Wyoming, considered to extend back to the Iowan. Correlation of results with the meticulous pollen analyses of Frey (1953) on the Carolina Bays was less successful. Frey suggests that the entire Wisconsin is compressed into about 4 m of peat, in comparison with the 48 m of inorganic sediments here assigned to the same length of time. Recently Wells and Boyce (1953) have reopened the problem of the age of the sediments of the Carolina Bays, questioning their continuity.

The conclusion of Bryan and Arellano that humid and arid conditions have alternated is confirmed, as is their judgment that the Caliche Barrilaco whose correlative sediment lies between 5 and 10 m, represents an arid period of retreat after the close of the Pleistocene proper, *i.e.*, the Mankato. The writers differ only in assigning the dark Totolzingo earth to a humid period often called the Cochrane, corresponding to the next-to-last secondary readvance (or pause), and in describing the period preceding the Latest or Little Glaciation as arid. As Bryan correctly says, the Noche Buena, or archeological soil overlying the Totolzingo, has included *fluctuationes de clima*.

We have not been able to account for all of the known events of the Pleistocene above the 33-m level or top of the Tarango formation, considered by these colleagues to represent the end of the Pliocene. Aside from this we have encountered nothing inconsistent with the idea that our two cores give a climatic record extending back to the early Wisconsin.

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Manuscript Received by the Secretary of the Society, May 20, 1954

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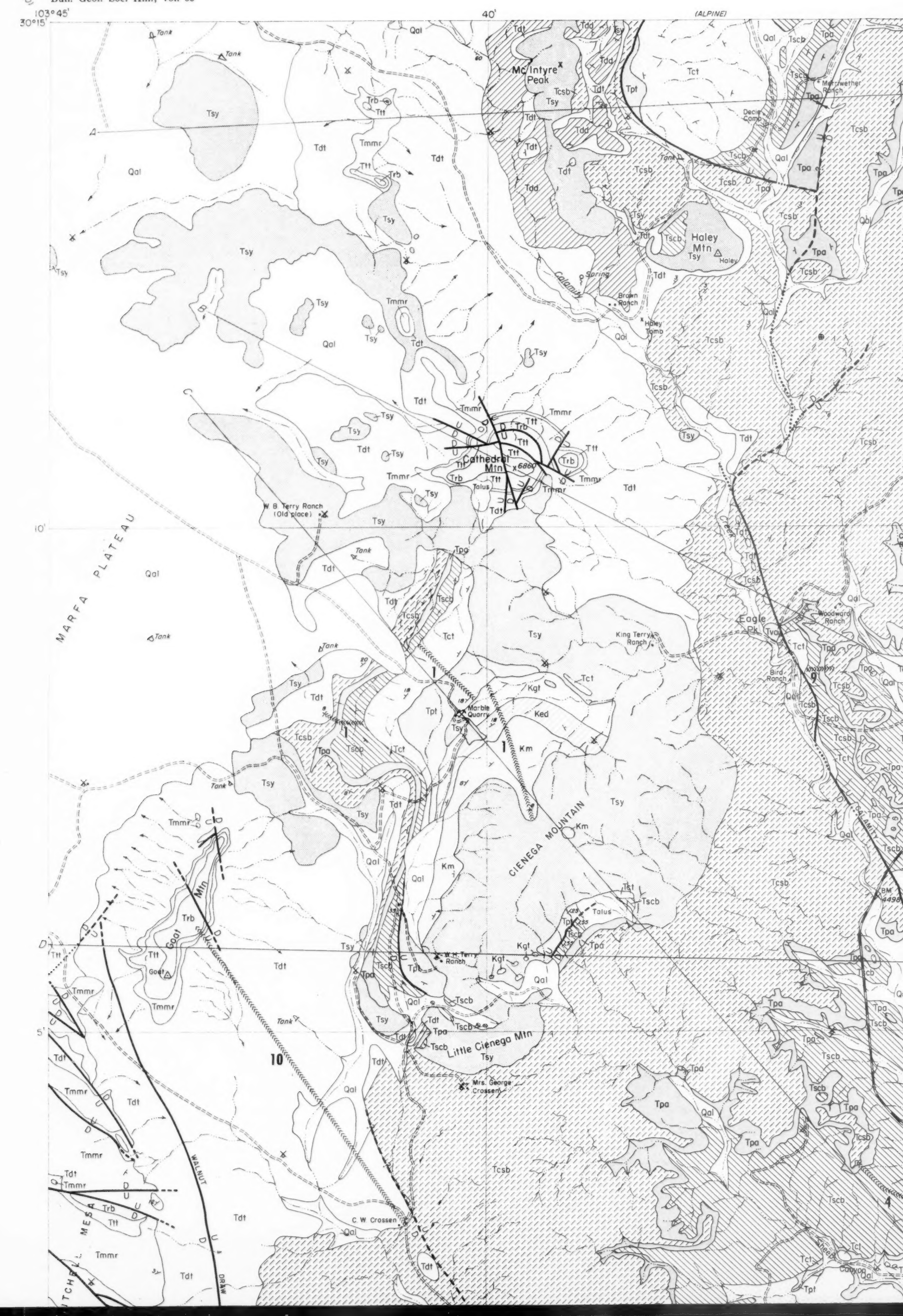
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Brown Ranch
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Decie Camp
Merriwether Ranch
Cathedral Mtn
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W B Terry Ranch (Old place)
Marble Quarry
King Terry Ranch
Eagle Pk
Woodward Ranch
Bird Ranch
CIENEGA MOUNTAIN
Little Cienega Mtn
Goat Mtn
Goat
W. H. Terry Ranch
Mrs. George Crossen
C. W. Crossen
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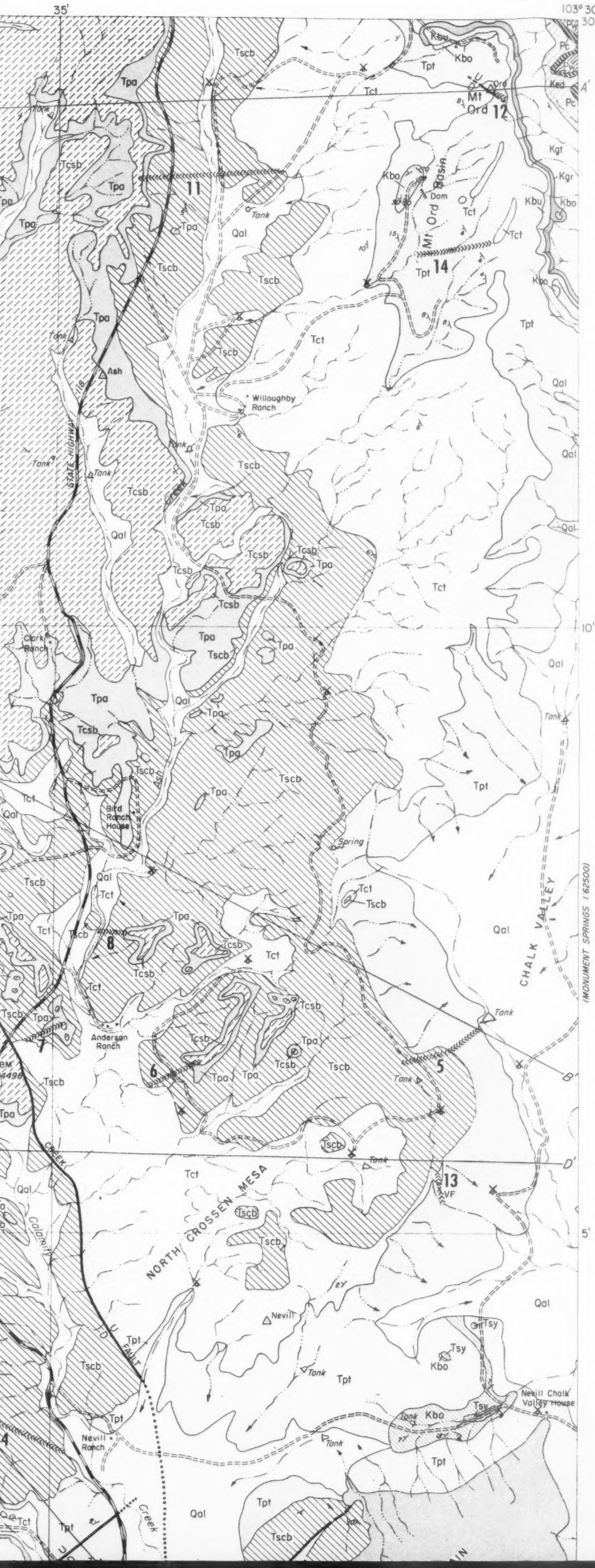


EXPLANATION

QUATERNARY

Qal — Alluvium

TERTIARY

Intrusive igneous rocks

Tva — Vent agglomerate

Tsy — Alkalic microsyenite

Trb — Rawls basalt
Fine-grained porphyritic and nonporphyritic flows and flow breccia; trachybasalt.

Ttt — Tascotal formation
Rhyolitic tuff, coarse sandstone, and conglomerate.

Tmmr — Mitchell Mesa welded tuff
Welded rhyolitic tuff.

Tdt (Tdd) — Duff formation
In south portion mainly rhyolitic tuff with a few thin sandstone, conglomerate and basalt interbeds; in northern part tuff, sandstone and conglomerate with Decie member (Tdd): trachyandesite, trachyte and rhyolite flows and flow breccias.

Buck Hill volcanic series

Tcsb — Cottonwood Spring basalt
Dense to vesicular and amygdaloidal flows; trachyandesite to trachybasalt.

Tpa — Potato Hill andesite
Massive flow and flow breccia, porphyritic and nonporphyritic facies.

Tscb — Sheep Canyon basalt
Porphyritic flows with thin intercalation of tuff and fresh-water limestone.

Oligocene and younger ?

Eocene

Tct — Crossen trachyte
Massive flow of porphyritic trachyte.

Tpt — Pruett tuff
Rhyolitic tuff with minor sandstone and conglomerate and considerable fresh-water limestone.

UNCONFORMITY

CRETACEOUS

Gulf series

Kbo — Boquillas formation
Alternating flaggy limestone and shale.

Kbu — Buda limestone
Massive limestone with middle marly unit.

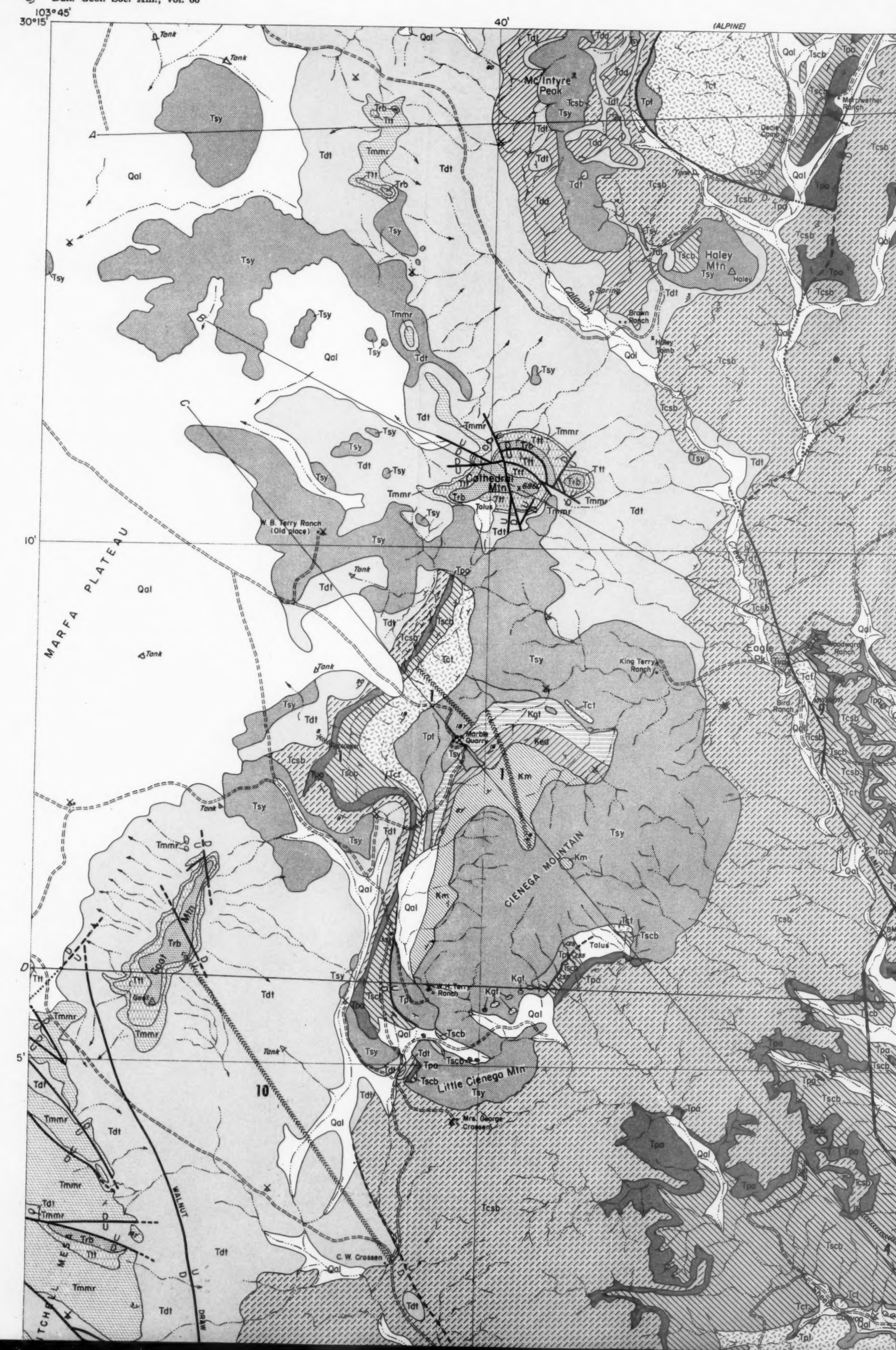
Comanche series

Kgr — Grayson marl (Del Rio)
Argillaceous marl with arenaceous limestone layers.

Kgt — Georgetown limestone
Massive limestone, more thinly bedded toward top.

Ked — Edwards limestone
Thick-bedded cherty limestone.

Km — Maxon (?) sandstone
Basal sandstone, shale, and conglomerate.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Tst
Tscb
Talus
Qbl
McIntyre Peak
Haley Mtn
Haley
Haley Tomb
Brown Ranch
Spring
Calamity
Cathedral Mtn
x6864
Talus
W. B. Terry Ranch (Old place)
Marble Quarry
King Terry Ranch
Eagle Pk.
Woodward Ranch
Bird Ranch
Merriweather Ranch
Decie Camp
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Little Cienega Mtn
Mrs. George Crossen
C. W. Crossen
Coal Mtn
WALNUT DRAW
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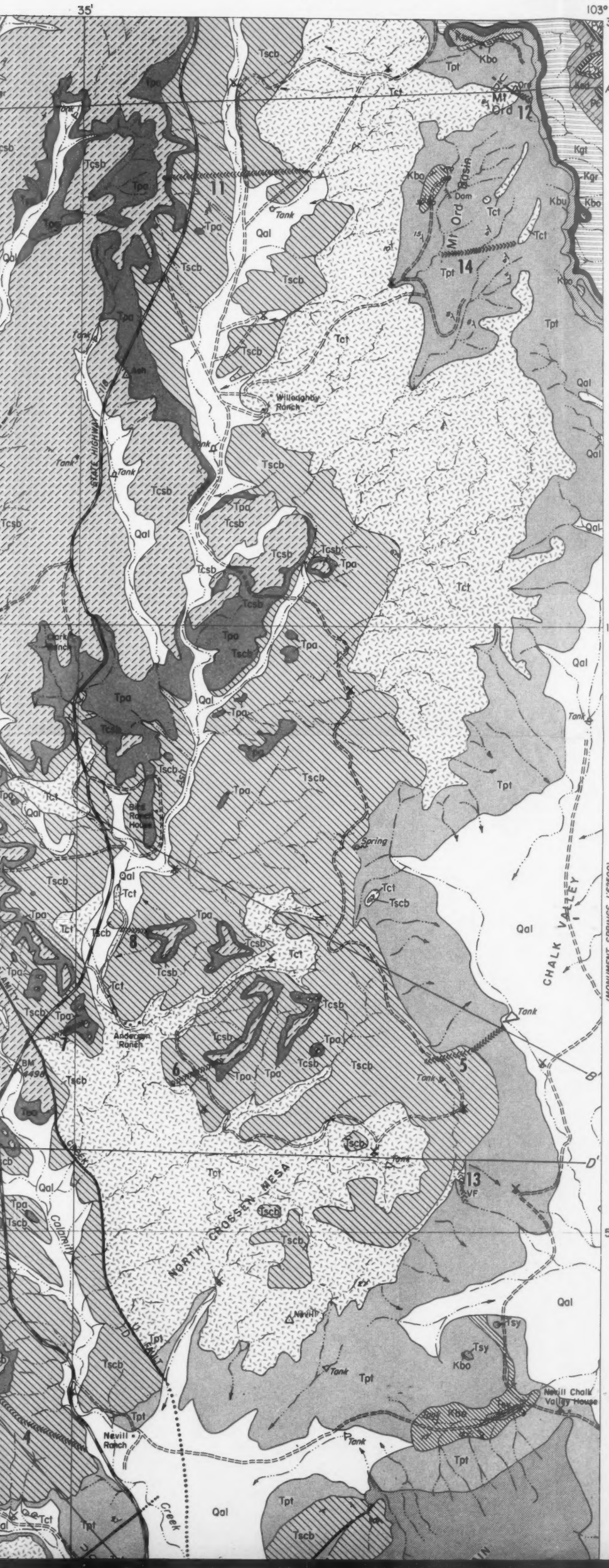

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Basal sandstone, shale, and conglomerate.

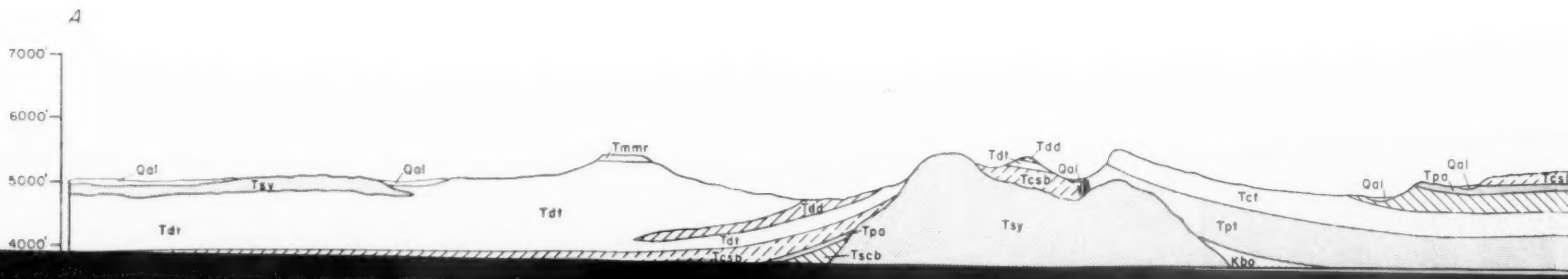
Base from United States Air Force photographs
Cartography by J. W. Macon

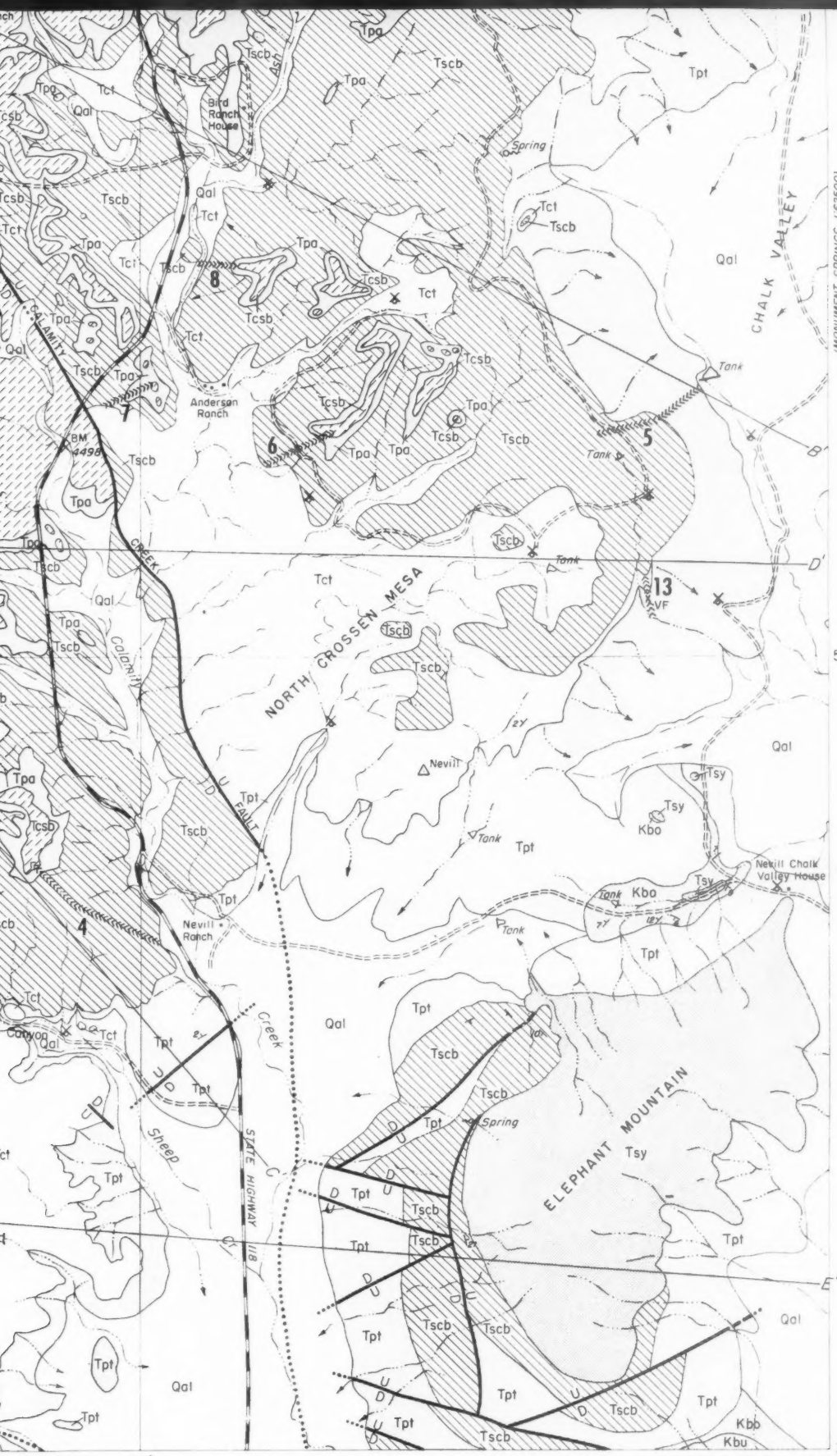
Scale 1:62500

APPROXIMATE MEAN DECLINATION 1953

GEOLOGIC MAP OF CATHEDRAL MOUNTAIN QUADRANGLE

WITH STRUCTURE SECTIONS





Polyconic projection. North American datum
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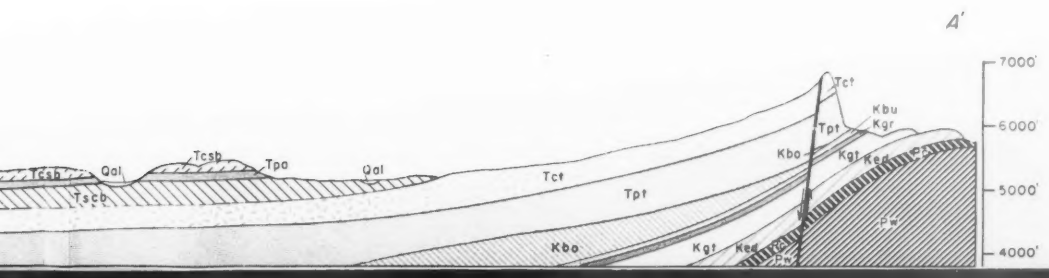
GLE, BREWSTER COUNTY, TEXAS



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Comanche series
CRETACEOUS

UNCONFORMITY

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Pw
Word formation
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Guadalupe series
PERMIAN

U / D
Normal fault
U, *upthrown side*, D, *downthrown side; dashed where inferred; dotted where concealed.*

Axis of syncline

Strike and dip of beds

VF
Vertebrate fossil location

Windmill

7
Line of measured section

Ash
Triangulation station

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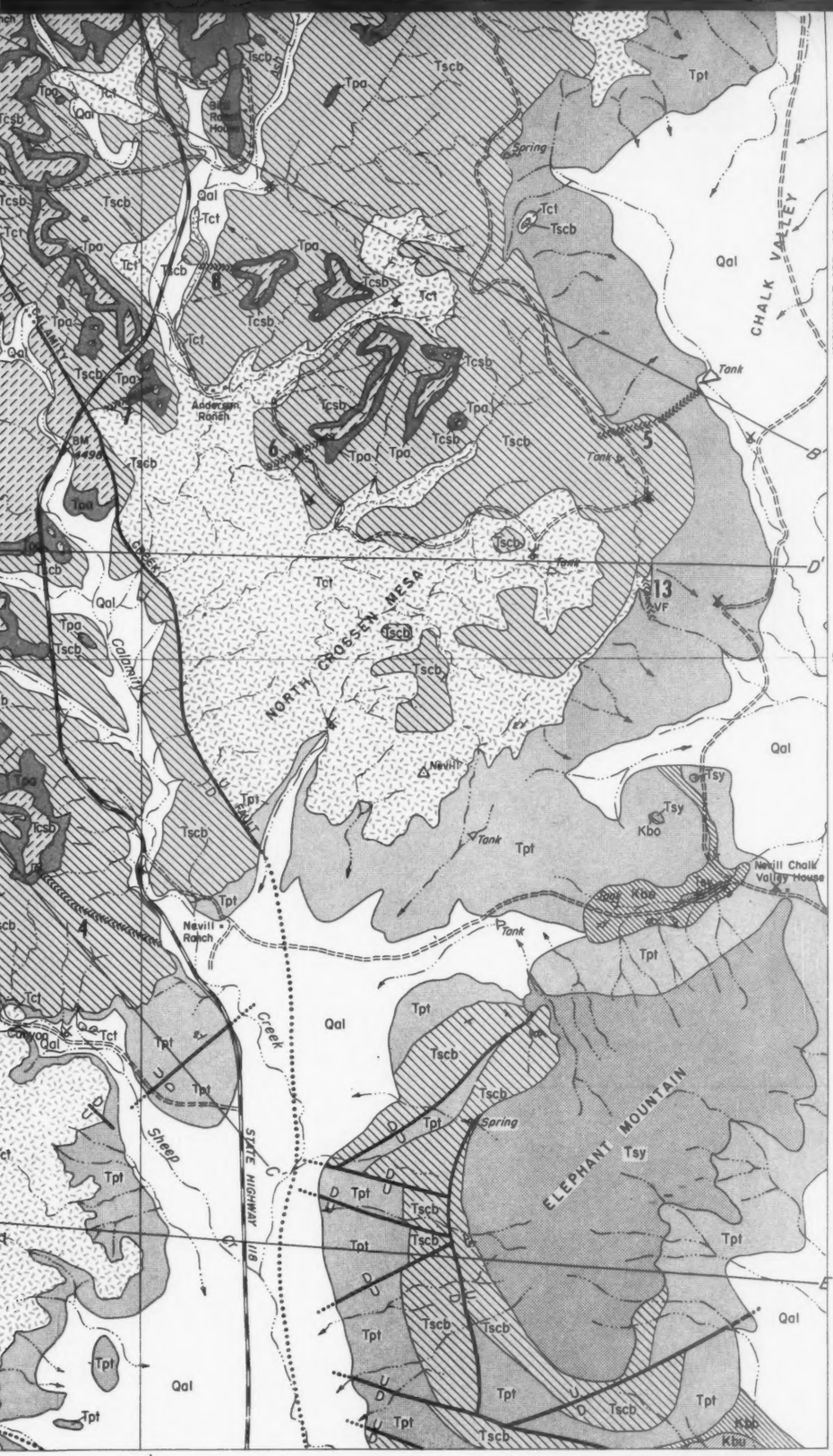
WITH STRUCTURE SECTIONS



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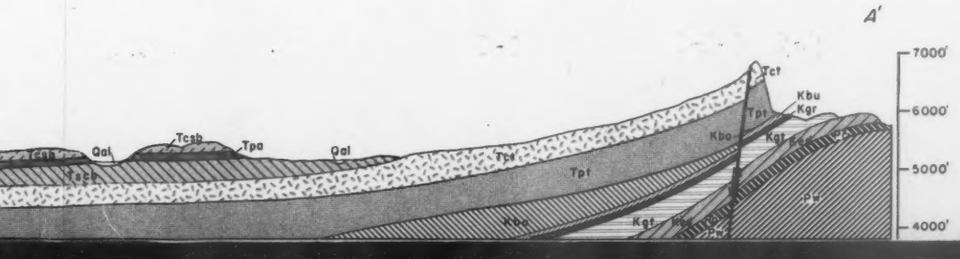

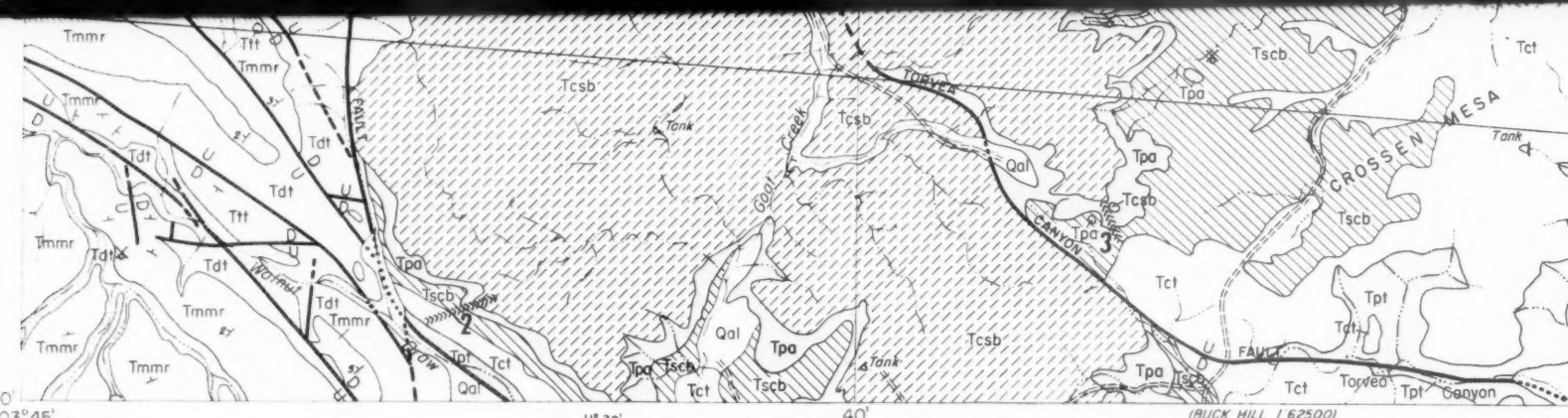

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APPROXIMATE MEAN
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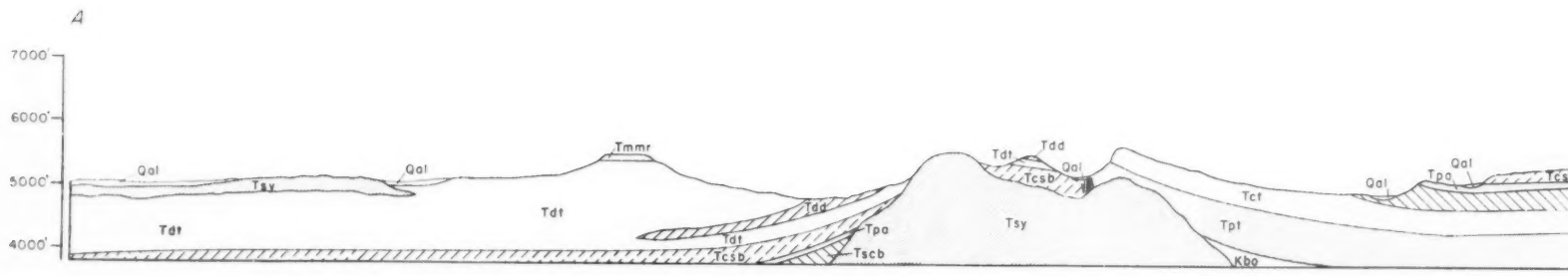

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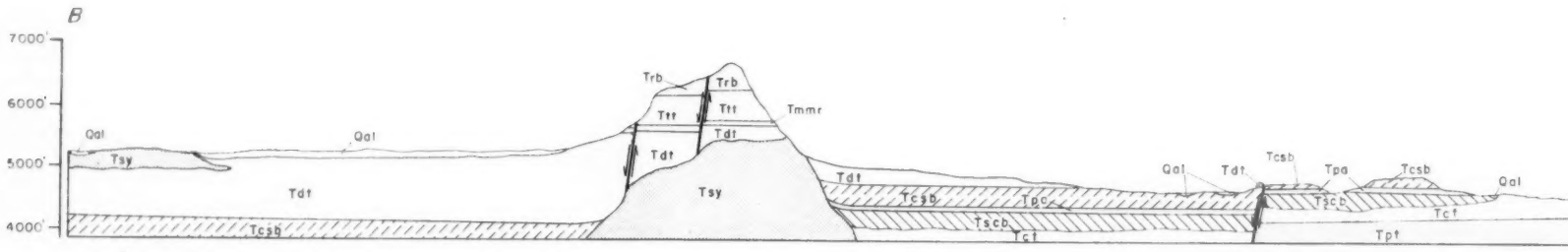

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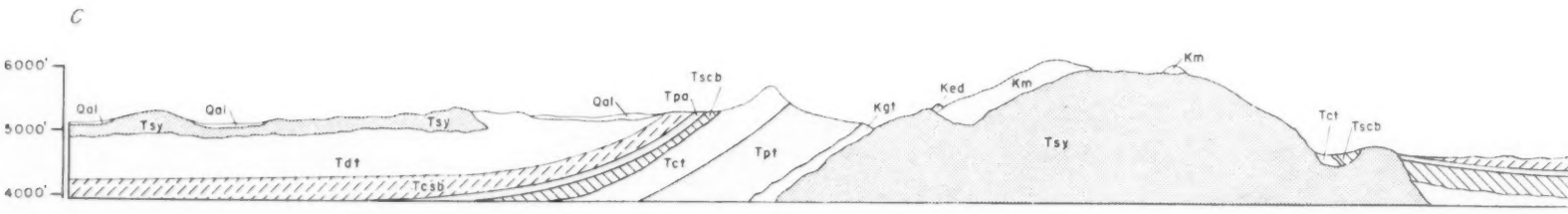

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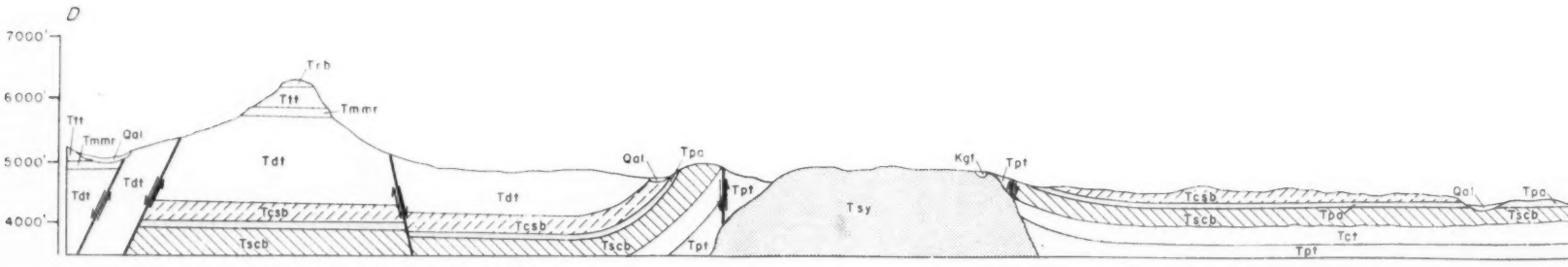

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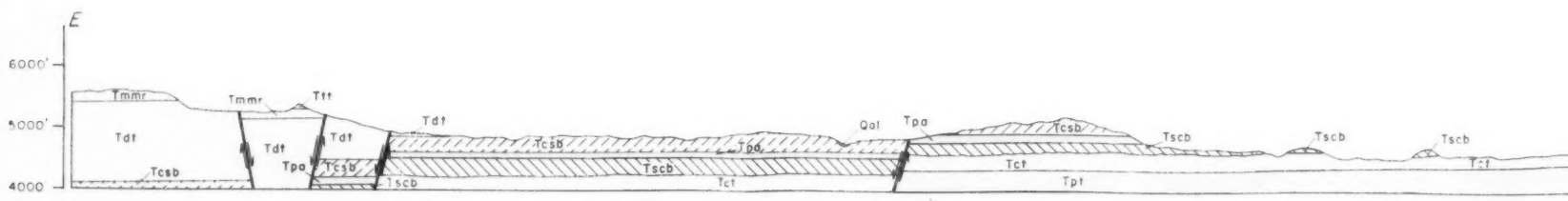

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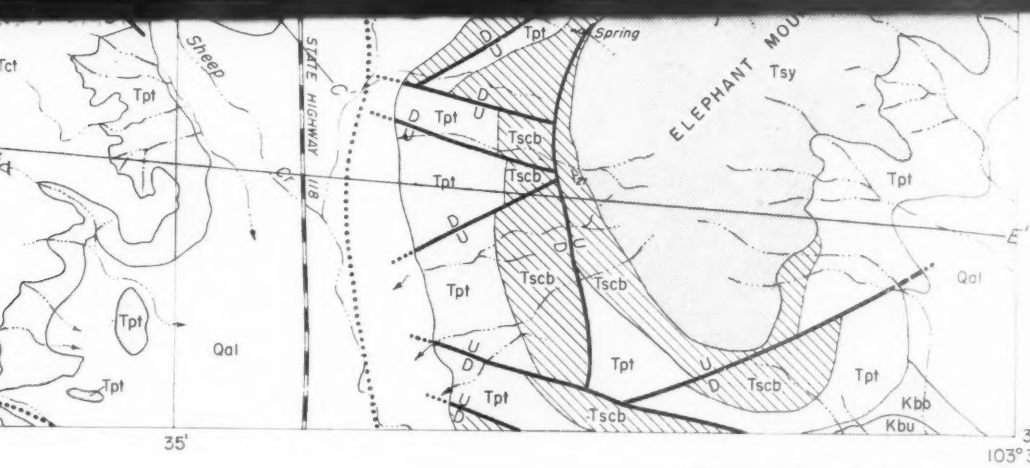

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ISANTIAGO PEAK 162500)

3 4 Miles

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UNCONFORMITY

Guadalupe series — PERMIAN

Pc — Capitan limestone
Massive dolomitic limestone.

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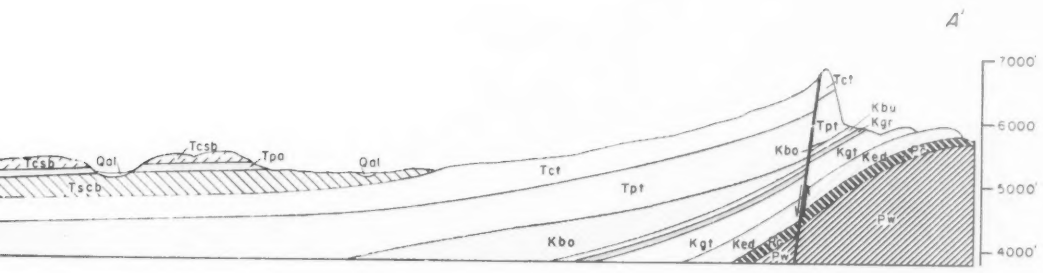

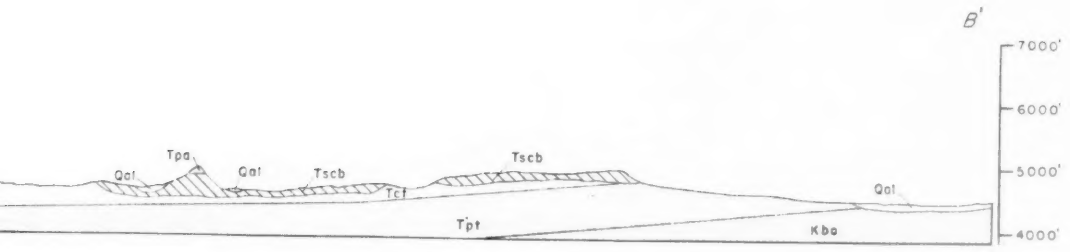

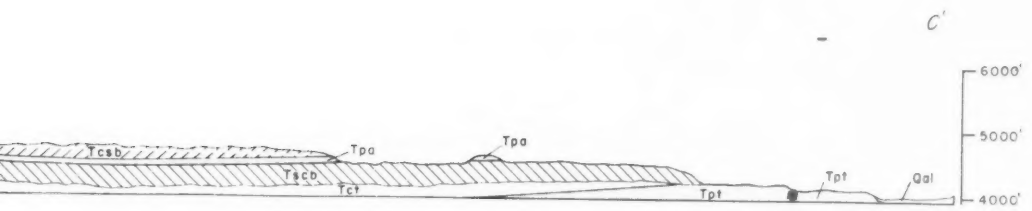

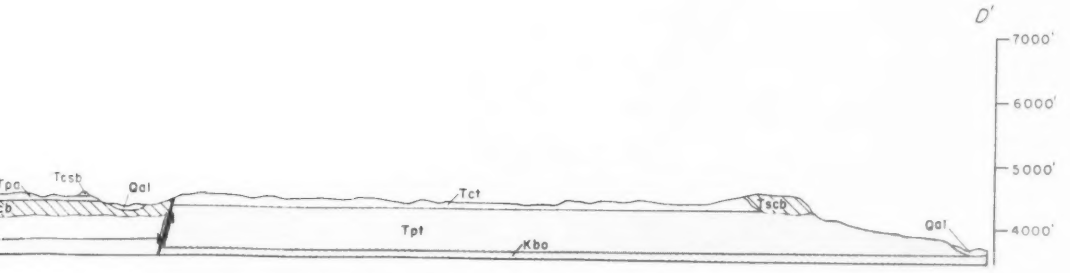

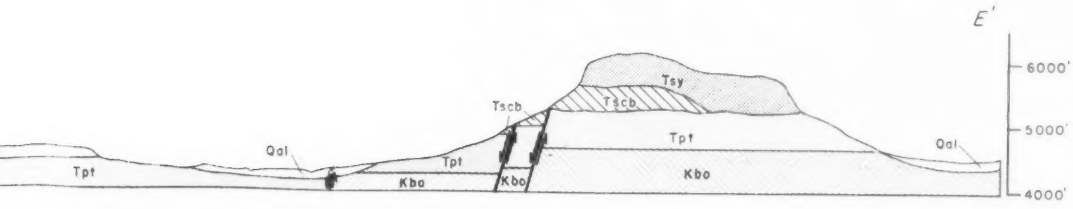

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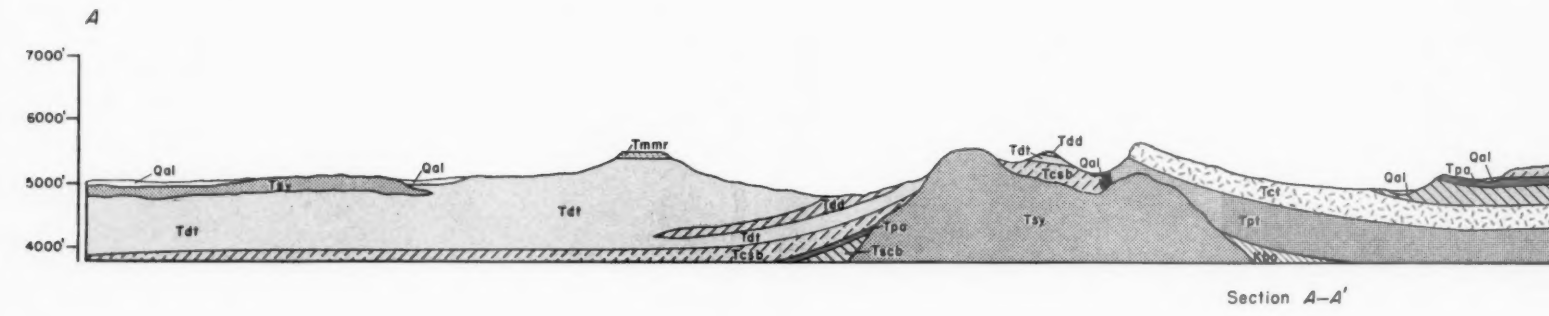

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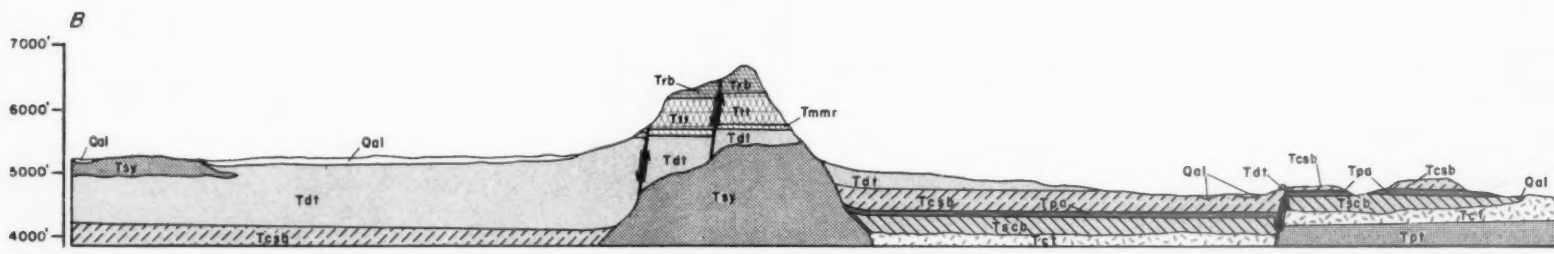

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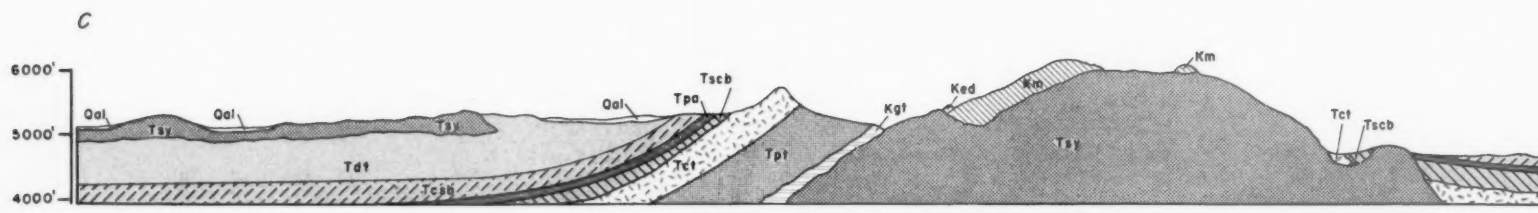

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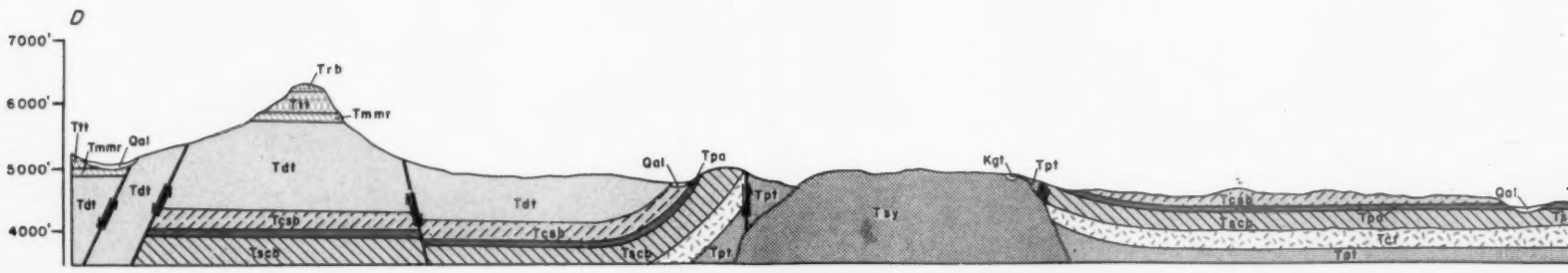

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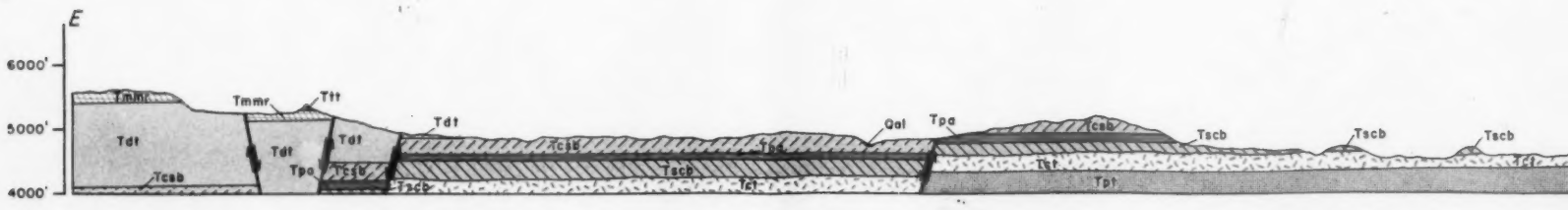

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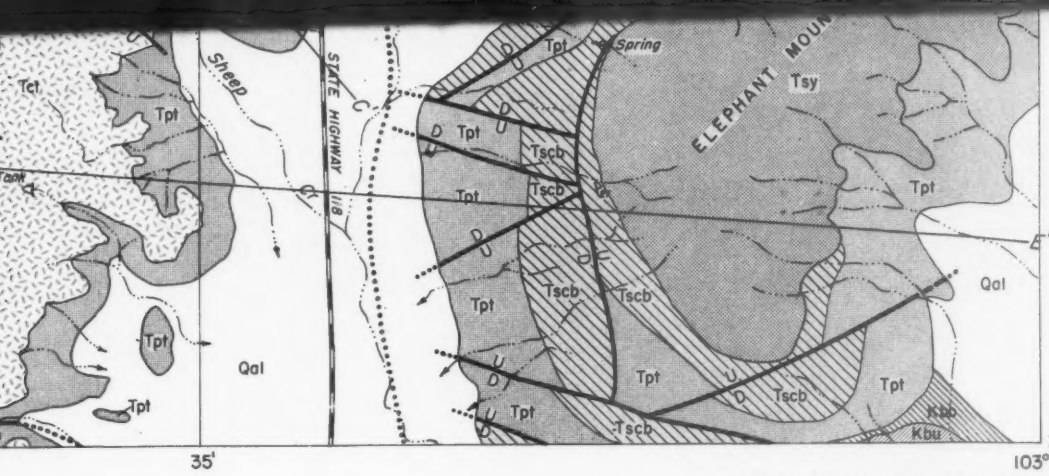

Polyconic projection. North American datum
Geology by W.N. McAnulty, Summers 1949-1951

ISANTIAGO PEAK 1:62500)

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15000 20000 Feet

5 Kilometers

UNCONFORMITY

Guadalupe series — PERMIAN

Pc — Capitan limestone
Massive dolomitic limestone.

Pw — Word formation
Sandstone, shale, and conglomerate.

U / D — Normal fault
U, *upthrown side*; D, *downthrown side; dashed where inferred; dotted where concealed.*

Axis of syncline

Strike and dip of beds

xVF — Vertebrate fossil location

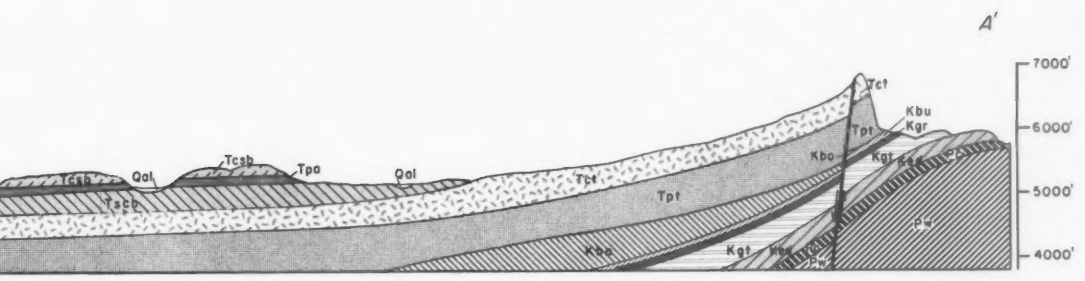
Windmill

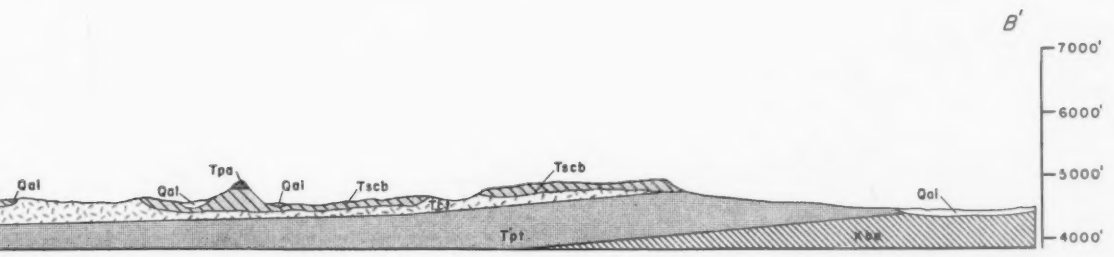
7 — Line of measured section

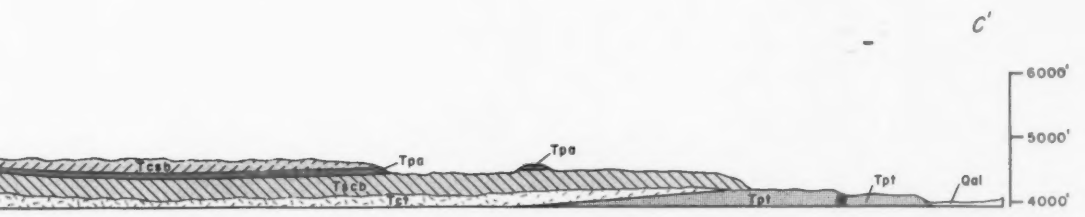
△Ash — Triangulation station

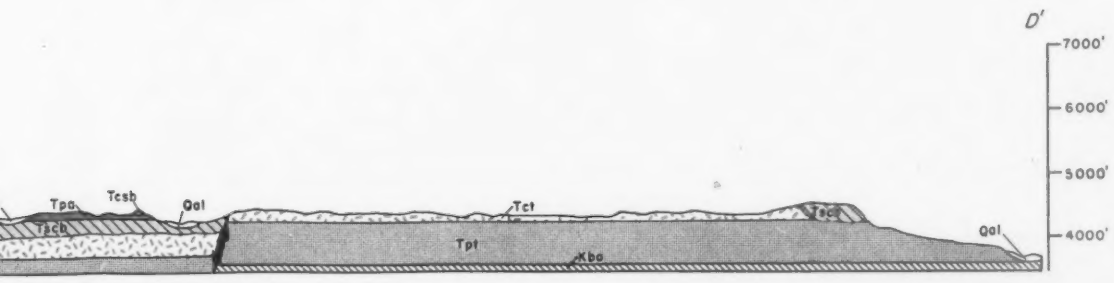
NGLE, BREWSTER COUNTY, TEXAS

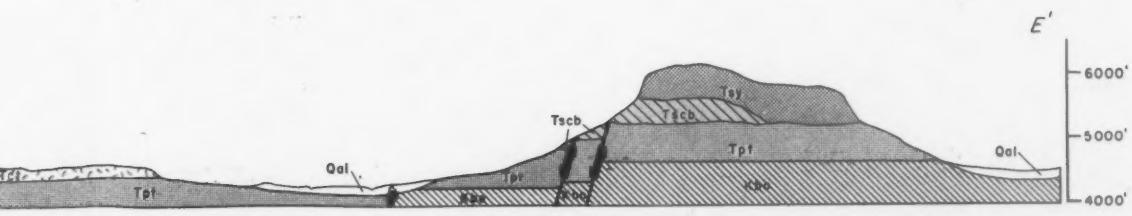
IS











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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 66, PP. 531-578, 3 FIGS., 3 PLS. MAY 1955

GEOLOGY OF CATHEDRAL MOUNTAIN QUADRANGLE, BREWSTER COUNTY, TEXAS

By William N. McAnulty

Abstract

Rocks exposed in the Cathedral Mountain quadrangle in the southeastern Davis Mountains of Trans-Pecos Texas are assigned to the Word formation and to Capitan limestone in the Permian Guadalupe series; to the Maxon sandstone, Edwards limestone, Georgetown limestone, and Grayson (Del Rio) marl in the Cretaceous Comanche series; to the Buda limestone and Boquillas limestone in the Cretaceous Gulf series; and to the Buck Hill volcanic series in the Tertiary. Volcanic rocks up to 4600 feet thick cover most of the quadrangle. The volcanic succession, similar to that in Buck Hill and other quadrangles to the south, is divided into the Pruett tuff, Crossen trachyte, Sheep Canyon basalt, Potato Hill andesite, Cottonwood Spring basalt, Duff formation, and Rawls basalt. Vertebrate fossils indicate a late Eocene (Duchesne) age for the Pruett tuff (restricted to the lowermost tuff, sandstone, and conglomerate beds). The top of the Eocene is placed at a prominent disconformity between the Crossen trachyte and the Sheep Canyon basalt; it is suggested the overlying lava and tuff layers are Oligocene and younger (?). Some of the many intrusive bodies of alkalic microsyenite which are younger than the volcanic rocks have effected much local deformation of the layered rocks. Quaternary alluvium is present along streams and over valley flats.

Northward across the quadrangle, the Crossen trachyte gains appreciable quartz, the Potato Hill andesite changes from highly porphyritic to nonporphyritic, and the Duff formation changes from dominantly rhyolite tuff to lava, tuff, and conglomerate (Decie member). Effects of five crustal disturbances—mid-Mesozoic, late Cretaceous, pre-upper Eocene, and three in the late Cenozoic—are apparent. Differential erosion of the intruded, folded, and faulted volcanic succession has roughened and diversified the landscape.

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INTRODUCTION

Location

The Davis Mountains in Trans-Pecos Texas lie at the intersection of Appalachian and Laramide lines of folding, across the connecting channel between the Permian Marfa and Delaware basins at the northern edge of the Mesozoic Coahuila peninsula between the Basin and Range and the Mexican Highlands physiographic provinces.

The Cathedral Mountain quadrangle (Fig. 1), an area of about 225 square miles in the southeastern part of the Davis Mountains, is the location under investigation. It is in northwestern Brewster County; the northern boundary is about 6½ miles south of Alpine (population 5000), county seat of Brewster County. State highway No. 118, from Alpine to Big Bend National Park, extends north-south near its eastern boundary. It is the southeastern quadrangle of the 30-minute Alpine quadrangle which has been divided by the U. S. Geological Survey into four 15-minute quadrangles—named Alpine in the northeast, Paisano Peak in the northwest, and unnamed in the southwest. In the text, the two Alpine quadrangles are designated as Alpine (30-min.) quadrangle and Alpine (15-min.) quadrangle.

Scope of Work

King studied the Glass Mountains (1930), outlined the structural development of Trans-Pecos Texas (1935), and mapped the Marathon and Monument Spring quadrangles (1937). Work by Lonsdale (1940) was the first comprehensive study of the igneous geology of Trans-Pecos Texas. Eifler mapped the Santiago Peak quadrangle (1943) and the Barrilla Mountains (1951). Goldich and Elms (1949) made a valuable contribution by working out the volcanic sequence in the Buck Hill quadrangle, and Goldich and Seward (1948) studied the northern part of the Jordan Gap quadrangle. Other recent workers in this region include R. R. Bloomer (1949, Ph.D. Dissertation, Univ. Texas) in the Christmas and Rosillos mountains, G. M. Stafford (open-file manuscript, 1952) in the Nine Point Mesa quadrangle, Erickson (1953) in the Tascotal Mesa quadrangle, Moon (1953) in the Agua Fria quadrangle, C. C. Rix (1953, Ph.D. Dissertation, Univ. Texas) in the Chinati Mountains, and Graves (1954) in the Hood Spring quadrangle.

Eighteen weeks were spent in the field mapping the Cathedral Mountain quadrangle—6 weeks each summer during 1949, 1950, and 1951. Approximately 6 weeks of reconnaissance mapping was done in the Alpine (15-min.) quadrangle in the spring of 1950 in connection with a ground-water survey for the city of Alpine (Fig. 2). All mapping was done on United States Air Force aerial photographs. The petrographic work and preparation of the manuscript were done at The University of Texas during the academic year 1952–53. The project is part of a West Texas region program of the Bureau of Economic Geology, The University of Texas.

ACKNOWLEDGMENTS

Dr. S. S. Goldich, formerly with the Bureau of Economic Geology, interested the writer in the problem and gave valuable assistance and encouragement. A better understanding of field relationships resulted from discussions in the field with Dr. J. T. Lonsdale, Director of the

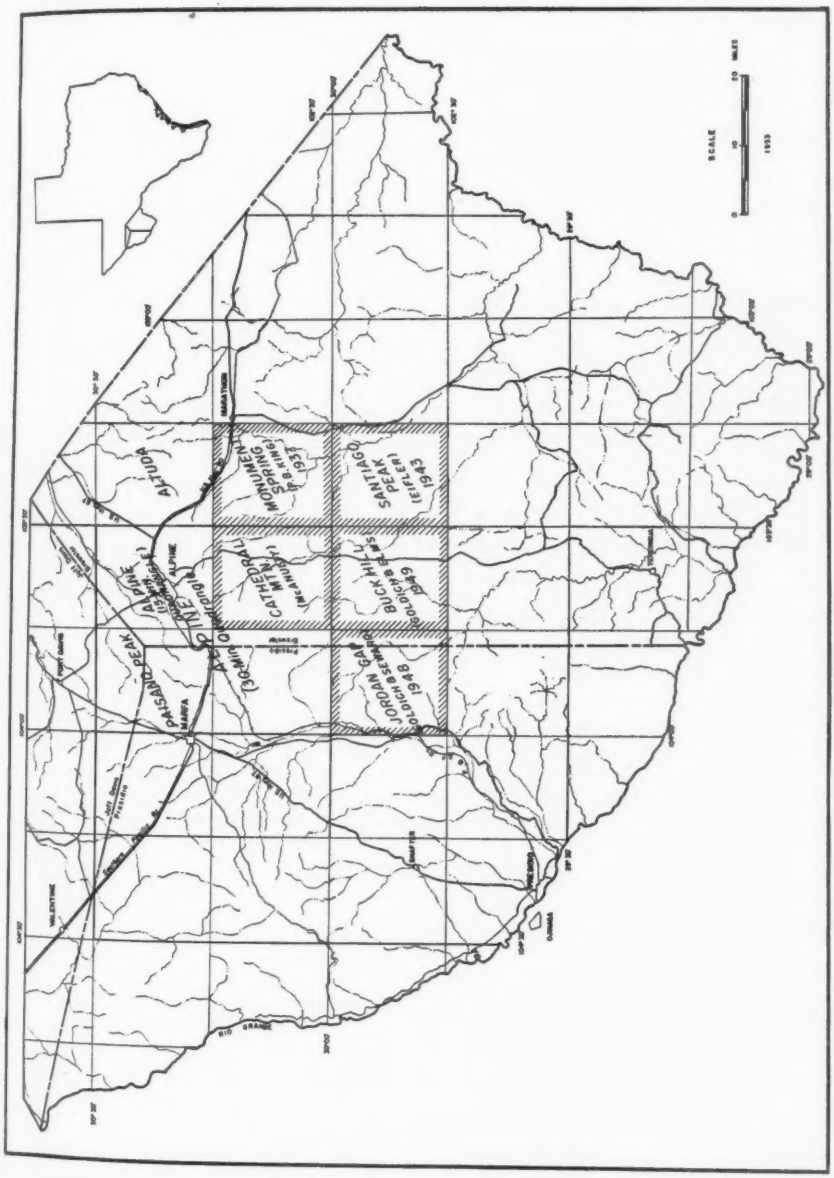

FIGURE 1.—INDEX MAP OF TRANS-PECOS TEXAS SHOWING LOCATION OF CATHEDRAL MOUNTAIN QUADRANGLE AND ADJOINING AREAS OF PUBLISHED MAPS

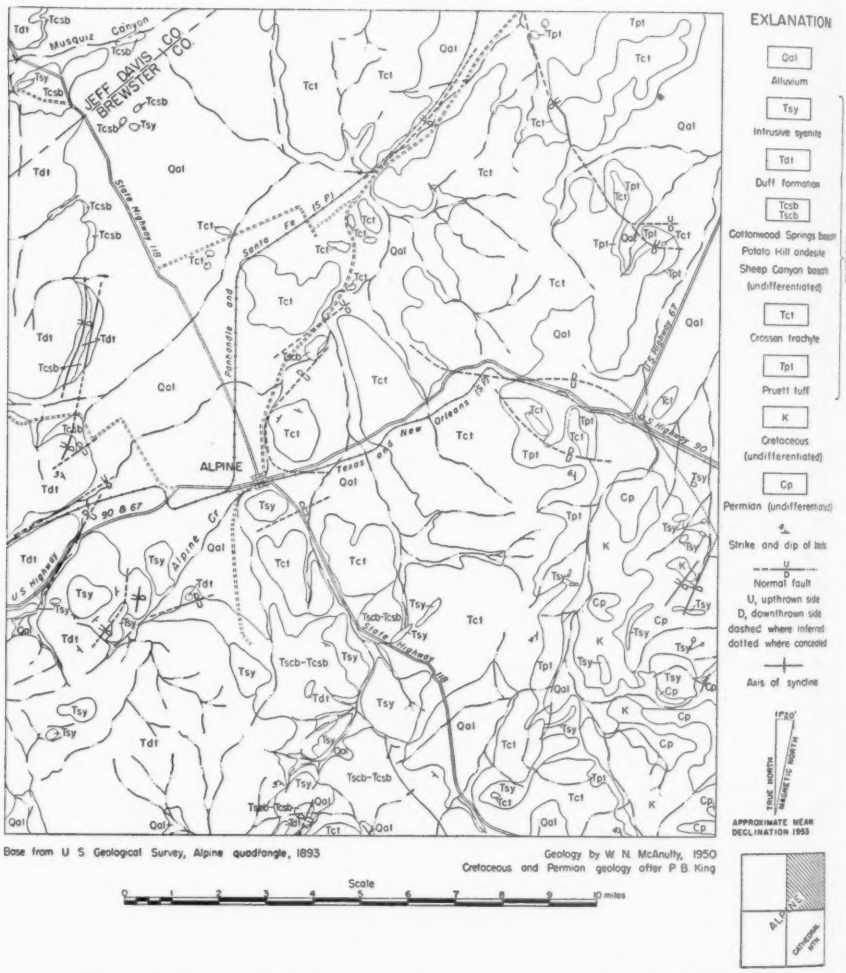

FIGURE 2.—GEOLOGIC RECONNAISSANCE MAP OF THE ALPINE (15-MIN.) QUADRANGLE, BREWSTER COUNTY, TEXAS

Bureau of Economic Geology, and Professor R. K. DeFord, The University of Texas.

Special credit is due Dr. S. E. Clabaugh, The University of Texas, for assistance in the petrographic studies, and for many helpful suggestions for the manuscript. Able assistance in the field was given by Frank Woodward, Jr., in 1949, Dennis R. Taylor in 1950, and Robert L. Wilson in 1951. David L. Amsbury helped identify the Cretaceous fossils.

Appreciation is expressed to the following ranchers and landowners in the area for their hospitality and co-operation: Messrs. W. L. Kokernot, Nevill Haynes, James Anderson, Frank Woodward, Sr., Ray Willoughby, Gay Merriwether, Zeb Decie, and W. C. Crossen, and to Mrs. Brown, Mrs. Clark, and Mrs. Crossen.

The manuscript, presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The University of Texas, May 1953, was reviewed by the graduate faculty

members of that university, R. K. DeFord, J. T. Lonsdale, S. E. Clabaugh, S. P. Ellison, and D. D. Brand. It was read also by Dr. S. S. Goldich of the University of Minnesota.

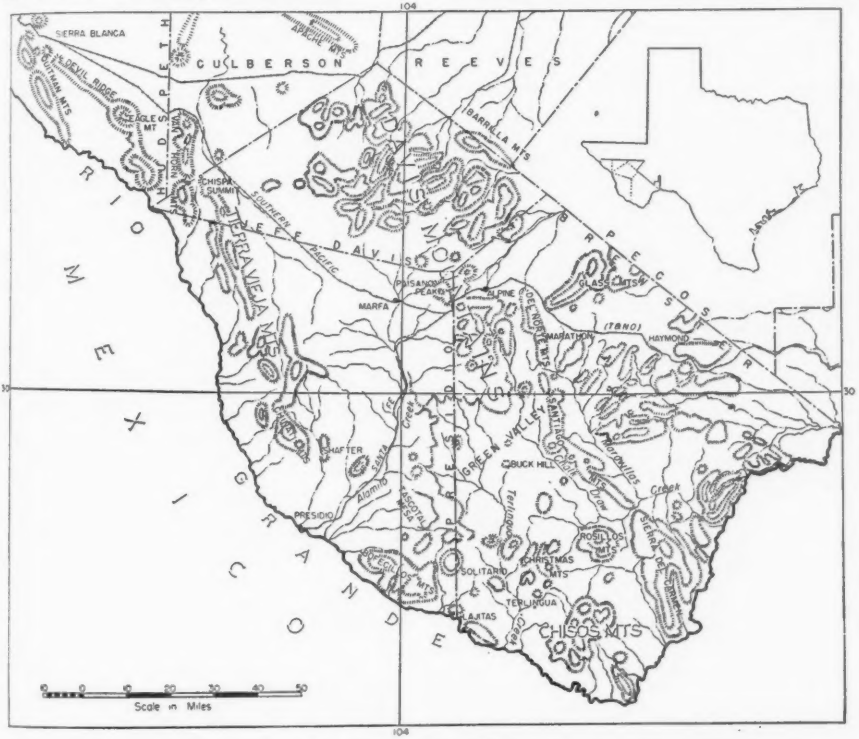

FIGURE 3.—SKETCH MAP OF A PART OF TRANS-PECOS TEXAS SHOWING PRINCIPAL PHYSIOGRAPHIC FEATURES

The Bureau of Economic Geology financed the field work, cost of thin sections, and drafting of the geologic maps. A scholarship granted by the Standard Oil Company of Texas made possible the residence work at the University.

REGIONAL SETTING

The Davis Mountains occupy an irregularly shaped area of approximately 1400 square miles in Jeff Davis, Brewster, and Presidio counties in west-central Trans-Pecos Texas. They lie at the north end of the Eastern Border Ranges division of the Mexican Highlands physiographic province (King, 1937, p. 2), which is bordered on the northwest by the Basin and Range province, on the northeast and east by the Great Plains province, and on the west by the western branch of the Sierra Madre Oriental of the Mexican Highlands province. Along the east side of the southern Davis Mountains are the Del Norte Mountains, which together with the Santiago Mountains to the south form the west side of the Marathon dome. These segments and the Sierra Del Carmen constitute a narrow, continuous range composed largely of folded and faulted Cretaceous limestone trending southwestward into northern Mexico.

The Davis Mountains are a highly dissected erosional remnant of a vast volcanic field that originally may have covered several thousand square miles in Trans-Pecos Texas and northern Mexico. During the Tertiary the thick volcanic succession accumulated in the northeastern part of an extensive structural depres-

TABLE 1.—GEOLOGIC FORMATIONS IN CATHEDRAL MOUNTAIN QUADRANGLE

Age	Group and Formation		Thickness (feet)	Lithology and Remarks
Quaternary	Alluvium		30±	Pleistocene and Recent valley fill and alluvium; unconsolidated silt, sand, and gravel
Tertiary	Buck Hill volcanic series	Rawls basalt	30–545	Very fine-grained, porphyritic flows of trachybasalt; massive, coarse flow breccia zones
		Tascotal formation	50–462	Light-gray and yellow rhyolitic tuff, coarse-grained sandstone and conglomerate
Oligocene and younger (?)		Mitchell Mesa welded tuff	58–134	Pink to gray, welded rhyolitic tuff
		Duff formation	1400–1500	Rhyolitic tuff, minor sandstone and conglomerate, two thin basalt flows in southern half; considerable sandstone, conglomerate, and thick basic and acidic lavas and flow breccias in north
		Cottonwood Spring basalt	220–332	Dense to vesicular and amygdaloidal flows of trachyandesite and olivine basalt; thick flow breccias
		Potato Hill andesite	35–190	Dark reddish-brown to gray porphyritic and nonporphyritic flow and flow breccia
		Sheep Canyon basalt	0–454	Porphyritic basaltic and trachyandesitic flows, separated by thin interbeds of tuff and fresh-water limestone
Upper Eocene (Duchesne)		Crossen trachyte	0–265	Massive flow of porphyritic trachyte
		Pruett tuff	474–798	Rhyolitic tuff, with sandstone, conglomerate, and considerable fresh-water limestone
	Angular unconformity			

TABLE 1.—*Continued*

Age	Group and Formation		Thickness (feet)	Lithology and Remarks
Cretaceous Gulf series	Eagle Ford group	Boquillas formation	0–75	Alternating shale and limestone flags
		Disconformity		
Comanche series	Washita group	Buda limestone	60–70	Thick-bedded limestone, with middle nodular marly member
		Disconformity		
		Grayson marl	10–20	Calcareous clay and marl, with flaggy sandy limestone
		Georgetown limestone	200±	Thick-bedded limestone, more thinly bedded in upper part
	Fredericksburg group	Edwards limestone	250±	Dense to marly, thin- to thick-bedded, cherty limestone
	Trinity group (?)	Maxon (?) sandstone	366±	Sandstone, shale, and conglomerate
Permian Guadalupe series	Capitan limestone		120±	Massive dolomitic limestone
	Word formation		1500±	Siliceous shale, sandstone, conglomerate, and thin-bedded limestone

sion bounded on the north by the Apache-Delaware Mountain uplift and on the east by the Marathon dome, and has subsequently been carved by differential erosion into a rugged mountainous terrain (Fig. 3).

STRATIGRAPHY

Permian System

General.—The most nearly complete, continuously exposed marine Permian section in North America is in the Glass Mountains, a few miles northeast of the Cathedral Mountain quadrangle. The upper part of the Permian system is exposed in the Del Norte Mountains; two formations (Word formation and Capitan limestone) outcrop near Mt. Ord in the northeast corner of the Cathedral Mountain quadrangle. The Del Norte-Glass Mountains Permian stratigraphy is complicated by facies changes—forereef to reef to backreef from southwest to northeast, respectively; the strata of the Del Norte Mountains were laid down in a forereef environment.

A study of the complex Permian stratigraphy in the Del Norte and Glass Mountains is a problem beyond the scope of this investigation. The writer's work on it was restricted to mapping the outcrops and a field examination of the lithology in the immediate vicinity of Mt. Ord. Detailed maps, cross-sections, and excellent discussions of the Permian in this region are contained in papers by King (1930, 1937, 1942).

Word formation.—In the Del Norte Mountains the Word formation reaches a thickness of about 1500 feet, but only the upper 325 feet is exposed in the Cathedral Mountain quadrangle. It contains limestone but is mostly

siliceous shale, sandstone, and conglomerate. The lower limestone units contain abundant *Parafusulina* as well as a brachiopod fauna (King, 1937, p. 102). No fossils were found in the upper part of the formation. The Word formation is early Guadalupian and is equivalent to the Brushy Canyon and Cherry Canyon formations of the Guadalupe Mountain (Adams *et al.*, 1949, p. 8).

Section of Word formation exposed in canyon wall about ¾ mile northeast of Mt. Ord

	Thickness (Feet)
Light-gray, fine-grained, thin-bedded dolomitic limestone containing small chert nodules, and interbedded siliceous shale	50
Light-brown, fine-grained, thin-bedded, argillaceous sandstone, and siliceous shale	85
Brown platy siliceous shale, with thin interbeds of dense limestone	90
Light reddish-brown, fine-grained, flaggy sandstone with interbedded siliceous shale	100
Total exposed thickness	325

Capitan limestone.—In the Mt. Ord area 120 feet of light-gray, massive dolomitic limestone conformably overlies the Word formation. Udden (1917, p. 50–52) placed this limestone in the lower part of his Vidrio formation. Stratigraphic terminology for west Texas Permian rocks has undergone several revisions, and the following names apply to this unit: "lower massive member" of the Capitan formation (King, 1930, p. 78), "Vidrio massive member" of the Capitan limestone (King, 1937, p. 105), and "Vidrio" (Adams *et al.*, 1949, p. 6). On the basis of fusulinid *Polydiexodina* in the rock, the writer mapped it as Capitan limestone.

An angular unconformity separates the Capitan limestone from the overlying Edwards limestone of Cretaceous age in this part of the Del Norte Mountains.

Cretaceous System

General.—All exposures of Cretaceous rocks are either at the base of the easternmost and southernmost erosional escarpments of the volcanic rocks or around laccolithic intrusions. The distribution of these exposures indicates that Cretaceous rocks probably underlie the Tertiary volcanic rocks throughout the quadrangle. The Cretaceous rocks are exposed more extensively in the Del Norte Mountains immediately to the east, in the escarpments flanking the Marathon dome, and in the region south of the Cathedral Mountain quadrangle.

The Boquillas limestone (Table 1) thins northward because of erosional truncation. Northernmost outcrops are discontinuous erosional remnants, whereas at the southern edge of the quadrangle the formation is much thicker and seems continuous. Beds between the Boquillas and the first lava flow, between the Del Norte Mountains and the Mt. Ord escarpment, are tuff and tuffaceous sedimentary rocks including beds of nonmarine limestones in the Pruett tuff. King (1937, p. 116) considered them equivalent to the Austin chalk or younger Cretaceous formations.

Maxon (?) sandstone.—The development of Cienega Mountain, a "trapdoor dome" type of laccolith in the west-central part of the quadrangle, produced several hundred feet of structural relief by arching Cretaceous strata and Tertiary volcanic rock over the central dome and on the northern and western margins. Except for one small knoblike remnant of sandstone and conglomerate at the southeast margin and a narrow arm of the same material ending in a peak on the northern edge, the original cover over the summit has been eroded to expose the syenite core. As the basal conglomeratic sandstone dips steeply away from the narrow northern summit, the outcrop widens down the north and west slopes, forming prominent curving cuestas trending down the slopes on the northwest and northeast. The conglomeratic sandstone is overlain by tilted Cretaceous limestone on the north and northwest, which in turn is overlain by Tertiary volcanic rock and alluvium along the west side of the mountain.

The lower part of the basal conglomeratic sandstone is exposed only rarely on the steep, debris-covered, upper slopes of the narrow summit ridge on Cienega Mountain; the upper portion is fairly well exposed in the inface of the cuesta swinging down and around the lower slopes. Poor exposures and the flexed attitude of the beds conforming to the domical shape of the syenite core make it difficult to ascer-

tain true thickness. The dip steepens from 8° in the summit area to about 18° on the lower slopes. As measured with a hand level and corrected for changing dips, the thickness is 366 feet.

The lower 300 feet is light-gray, fine-grained, well-cemented quartz sandstone, containing thin beds of gray, slightly calcareous argillaceous sandstone and arenaceous shale, and lenses of medium- to very coarse-grained quartz sandstone and granule-and-pebble quartz conglomerate. Numerous pea-sized quartz and chert pebbles are scattered through the shaly layers. The upper 66 feet consists mostly of gray to pink, medium- to very coarse-grained, well-cemented quartz sandstones and granule, pebble, and cobble quartz conglomerate. Conglomeratic lenses are most numerous and coarser in the upper part; the lower portion contains more fine-grained sandstone and argillaceous material. In the conglomerate the granules, pebbles, and cobbles of white vein quartz, brown quartzite, and black and varicolored chert are well rounded.

No fossils were found in this formation. It is assigned to the Cretaceous because it is beneath Cretaceous limestone, and because basal Cretaceous conglomeratic sandstone is known in the Del Norte and Glass mountains and in the Solitario. There is little reason to doubt that these beds are Cretaceous, but whether they are Fredericksburg or Trinity is undetermined.

At Mt. Ord, Permian limestone underlies Edwards limestone. Near Black Peak, a few miles to the southeast in the Del Norte Mountains, the Edwards rests on cross-bedded conglomeratic sandstone, which grades southeastward into marly limestone containing Walnut and Comanche Peak (Fredericksburg) fossils. This suggests a Fredericksburg age for the basal conglomeratic sandstone at Cienega Mountain, but in the Glass Mountains lithologically similar beds are laterally continuous with the Maxon sandstone which King (1937, p. 114) placed at the top of the Trinity group. The Cienega Mountain section is thicker than basal beds in the neighboring areas, but perhaps this thickening should be expected immediately west of the Marathon dome, an area probably topographically and structurally low during the first inundation by the Cretaceous sea. The Cienega Mountain section may be partly Trinity and partly Fredericksburg in age.

Edwards limestone.—The 248-foot-thick Edwards limestone, exposed near Mt. Ord in the extreme northeast corner of the Cathedral Mountain quadrangle, is composed of light-gray, dense to marly, thin- to thick-bedded limestone separated by thin layers of soft marl. The limestone beds contain much brown, nodular chert; various types of rudistids and chamids occur in the more massive strata. At the base of the formation is a thin (less than 1 foot) limestone conglomerate. In this vicinity and northward in the Del Norte and Glass mountains, the Edwards contains more marl and marly limestone and has a less reefy appearance than in the Del Norte and Santiago mountains on the southeast. Near Mt. Ord and in the northern Del Norte Mountains the Edwards rests on the Capitan limestone and is overlain by Georgetown limestone.

Overlying the basal Cretaceous conglomeratic sandstone on the north and northwest slopes of Cienega Mountain is approximately 425 feet of metamorphosed, marine fossiliferous limestone assigned to the Edwards and Georgetown formations. It is about as thick as the combined Edwards and Georgetown near Mt. Ord. The beds are tilted 12°–18° away from the Cienega Mountain laccolith. On the northeast and east, where the limestone is in contact with the Cienega Mountain syenite mass, two bosses on the large intrusion cut the limestones in the central part of the outcrop area. Contact metamorphic effects range from slight baking effects to dark coarsely crystalline marble and friable sugary limestone.

The lower 250 feet of the section equivalent (?) to Edwards consists of light-gray to black (in places mottled), finely crystalline limestone in beds a few inches to 4 feet thick, separated by thin layers of yellowish marl. Considerable chert, in the form of narrow stringers, irregular-shaped nodules, and thin discontinuous layers along bedding planes, occurs in the limestone beds, and narrow calcite veins are numerous along joints and fractures. The limestone strata are highly fossiliferous but so altered that it is

practically impossible to collect identifiable specimens.

Georgetown limestone.—Around Mt. Ord the Georgetown limestone ranges from 210 to 253 feet in thickness and is composed of buff to gray, fine- to coarse-grained, nodular and marly, fossiliferous limestone in beds a few inches to a few feet thick. Two massive members, one near the middle and one toward the top, tend to form prominent ledges. King (1937, p. 115) suggested that these two ledge-making members correlate with the "middle cap rock" and "upper cap rock" of the Fort Stockton district, and Adkins (1927, p. 57–58) suggested that the lower member is "of approximately Denton age" and that the upper one could be correlated provisionally with the Main Street of central Texas. The upper massive member contains much brown ovoid chert, and some zones are crowded with rudistids and Gryphaeas. The formation contains many fossils, but identifiable specimens are not easy to obtain. These genera and species were collected:

Gryphaea mucronata Gabb
Protocardia multistriata
Pecten georgetownensis (?) Kniker
Pecten (*Neithea*) aff. *duplicosta*
Marcocallista (?) sp.
Toucasia sp.
Kingena wacoensis (Roemer)

The upper 175–200 feet of metamorphosed limestone strata exposed on the north and northwest slopes of Cienega Mountain is believed to represent the Georgetown limestone. The beds are highly fossiliferous, containing rudistids, chamids, gastropods, oysters, and clams, but no index fossils were collected. In the contact aureole around the larger of two syenite masses cutting the limestone, a marble quarry was opened several years ago. The quality of the stone is fairly good, but the dark color is not particularly attractive, and the project failed for the lack of a market.

There are several small, isolated patches of Cretaceous limestone low on the south slope of Cienega Mountain with fossils similar to those found in the strata assigned to the Georgetown on the opposite side of the mountain. These blocks were dragged up from below by the syenite mass upon which they now rest.

The Georgetown limestone in the Mt. Ord area lies disconformably (?) on the Edwards limestone and is conformably overlain by the Grayson marl. On the northern slopes of Cienega Mountain it rests on Edwards and/or intrusive syenite and is capped by Pruett tuff. Although the fossiliferous Kiamichi clay and marl, an easily recognized unit between the Edwards and Georgetown on the east and southeast flanks of the Marathon dome, cannot be distinguished here, careful paleontologic work might show the presence of equivalent limestone beds.

Grayson (Del Rio) marl.—Near the base of the prominent Mt. Ord escarpment in the northeast corner of the quadrangle, conformably on Georgetown limestone and disconformably below Buda limestone, is the Grayson marl—10–20 feet of soft, yellow greenish-gray, laminated to massive, fossiliferous, calcareous clay and marl containing thin, rusty brown flags of sandy limestone crowded with the large agglutinated foraminifer *Haplostiche texana* (Conrad). Exposures along the steep debris-strewn slopes are not numerous but are frequent enough to indicate that the formation is continuous. Exposures are better on the more gentle slopes of the Del Norte Mountains across Chalk Valley to the southeast (in Monument Spring quadrangle)—a southeastward extension of the outcrop in the Mt. Ord area. The marl can be seen also in discontinuous outcrops northward from Mt. Ord to the northern extremity of the Del Nortes. Fossils found in the Grayson in the Mt. Ord area are:

Haplostiche texana (Conrad)
Gryphaea sp.
Exogyra arietina Roemer
Exogyra cartledgi Böse

Buda limestone.—Buda limestone crops out near the base of the escarpment around Mt. Ord and at the foot of Elephant Mountain; the best exposure in the northeast corner is on the north side of Mt. Ord. Near the base of the east-facing Mt. Ord escarpment float from the overlying Pruett tuff obscures the outcrop.

The Buda limestone has a distinctive lithology. Where fully exposed it nearly always shows three members: (1) a lower; gray, thick-

bedded, fine-grained, brecciated limestone, (2) a middle; gray, nodular, fine-grained limestone and buff to gray, thin-bedded, fine-grained fossiliferous marl, and (3) an upper; light-gray to white, porcelaneous, thick-bedded, brecciated limestone. Its 60–70-foot thickness is uniform over a wide area, measuring 68 feet at Mt. Ord and 65 feet at Elephant Mountain. Fossils are abundant in the Buda, especially in the middle nodular and marly member. The fossils collected were:

Turritella budaensis Shattuck
Alectryona sp.
Gryphaea graysonana Stanton
Lunia wacoensis Roemer
Cardium (*Protocardia*) sp.
Pecten (*Neithea*) *texanus* Roemer
Pecten (*Neithea*) *whitneyi* Kniker
Pholodomya roemeri (?)
Stoliczkaia n. sp.
Hemiaster calvini Clark
Heteraster sp.
Budaiceras sp.

The wavy contact between the Buda and the underlying Grayson marl suggests a disconformity. At Elephant Mountain the Buda is overlain disconformably by the Boquillas limestone; in the Mt. Ord area it is capped by erosional remnants of the Boquillas and/or Pruett tuff.

Boquillas limestone.—A flaggy limestone facies of the Boquillas formation represents the Gulf series. There are several isolated outcrops of small areal extent in the southeastern and northeastern corners of the quadrangle. Better exposures with greater thicknesses occur along the west slopes of the Del Norte and Santiago mountains in Monument Spring and Santiago Peak quadrangles and to the south in Buck Hill and Agua Fria quadrangles.

The lithology—thin limestone flags and interbedded shale—is similar to that of the type Boquillas near Hot Springs in Big Bend National Park. The flaggy beds are light-gray to brown, fine-grained, fossiliferous limestones of varying purity in layers from 1 to 6 inches thick. Some strata are hard, nearly pure limestone; others are chalky and contain much fine sand and clay material. Banding caused by limonite staining is common. The flags tend to weather into small rectangular blocks. Partings of soft, gray to brown, laminated shale, sandy clay, and marl from a fraction of an inch to a foot or more in thickness separate the limestone beds. Boquillas limestone crops out discontinuously along the lower slopes of the escarpment around Mt. Ord. Because wash and gravity-moved materials from the overlying volcanic rocks cover most of the slope, good exposures are rare; and although these few outcrops appear to be only isolated erosional remnants, a thin layer of Boquillas could well be present all along the escarpment between the Buda limestone and the Pruett tuff. The formation has been traced from one small outcrop to another, along the base of the eastern edge of the Tertiary volcanic rocks to the northeast corner of the Alpine (15-min.) quadrangle, approximately 15 miles north of Mt. Ord. The broken and tilted attitude of the Boquillas beds—deformation not reflected in the underlying formations—strongly suggests that these small outcrops are discontinuous and were outliers on the Buda limestone at the beginning of the deposition of the overlying Pruett tuff. The deformation is of a type that could be produced by sliding or tumbling of large blocks down a slope or by slumping into a solution cavity. The thickest outcrop along the Mt. Ord escarpment, on the north side of Mt. Ord, is approximately 75 feet; other outcrops measured range from a few feet up to 50 feet in thickness.

A small mass of Boquillas limestone is exposed in the northern part of the Mt. Ord basin immediately southwest of Mt. Ord. Its structure is domical, with the beds dipping sharply (20°–70°) in all directions. Whether this outcrop represents a hill on the old pre-Tertiary erosional surface or the top of a small covered laccolith is not known; lack of metamorphism of the limestone or observable deformation of the overlying tuff suggests the former.

The Boquillas outcrop in the low area between Elephant Mountain and North Crossen Mesa is associated with an igneous intrusion. A boss on the syenite mass which supplied the thick sill capping Elephant Mountain arched the Boquillas and overlying Tertiary volcanic rocks. This small laccolithic structure was later breached by erosion, exposing tilted beds of Pruett tuff, Boquillas limestone, and small

areas of the syenite core. The Boquillas is in direct contact with the syenite and has been slightly metamorphosed; the limestone is dark gray to black and the shale is purplish. The thickest section, about 53 feet, is exposed along a small creek in the eastern half of the main outcrop area.

Outcrops of Boquillas and Buda limestones cover a small area near the foot of Elephant Mountain in the southeast corner of the quadrangle, the northern margin of a larger area of outcrop in the northeast corner of Buck Hill quadrangle. Study of the Cretaceous beds in this area is difficult because debris from the overlying volcanic rocks covers the slope of Elephant Mountain. Goldich and Elms (1949, p. 1177–1178) measured a section of Buda and Boquillas south of the quadrangle boundary (beginning in a gully 3 miles northeast of Kokernot ranch house) which has 38 feet of gray, massive Buda limestone and 117 feet of Boquillas. Their Boquillas section includes 64 feet of lower flaggy beds and 53 feet of upper limestone beds. On the basis of Foraminifera, Goldich and Elms (1949, p. 1143) correlated the upper 53 feet of beds with the lower Austin. Only the lower flaggy section is known in the Cathedral Mountain quadrangle.

These fossils were collected from outcrops of Boquillas limestone on the north side of Elephant Mountain and in the Mt. Ord area:

Inoceramus dimidius White
Inoceramus inconstans Woods
Inoceramus inconstans striatus Mant.
Inoceramus fragilus Hall and Meek
Inoceramus labiatus Schlotheim
Coilopoceras (?)

Tertiary System

General.—Volcanic rocks of Tertiary age, aggregating more than 4600 feet, including basaltic, andesitic, trachyandesitic, trachytic, and rhyolitic lavas, and thick tuffs and tuffaceous rocks containing sandstone, conglomerate, and nonmarine limestone, overlie marine Cretaceous rocks; their outcrops occupy more than 90 per cent of the quadrangle. Also, fairly large areas of tabular and domical intrusive masses of alkalic syenite are exposed at several places. The volcanic rocks are divided into nine formations, which are from oldest to youngest: Pruett tuff, Crossen trachyte, Sheep Canyon basalt, Potato Hill andesite, Cottonwood Spring basalt, Duff formation, Mitchell Mesa welded tuff, Tascotal formation, and Rawls basalt. The grouping and nomenclature follows, with minor modifications, the work by Goldich and Elms (1949, p. 1143–1163).

Little was known about these rocks in the Davis Mountains and adjacent areas to the south before the original work of Goldich and Elms (1949, p. 1143–1163) in Buck Hill, northern Jordan Gap, and southern Cathedral Mountain quadrangles. They applied the name Buck Hill volcanic series to the 3000–4000 feet of volcanic rocks resting unconformably on marine Cretaceous strata in the area between the Alpine intrusive igneous center on the north and the Terlingua center to the south. To a succession of five lavas alternating with five tuffs, some of which contain sandstone, breccia, conglomerate, and limestone, 1500–1700 feet thick, resting on Gulf rocks in the northeastern Davis Mountains (Barrilla Mountains), Eifler (1951, p. 342) gave the name McCutcheon volcanic series and divided it into three formations named, from oldest to youngest, the Huelster formation, Star Mountain rhyolite, and Seven Springs formation. There are considerable differences, both in thickness and lithology, between the Buck Hill and the McCutcheon series. These two successions represent conditions at opposite edges of one great volcanic field, and their relations will probably show clearly when the central Davis Mountains have been studied. The volcanic rocks which cover the Cathedral Mountain quadrangle are typical of the Buck Hill series; toward the north, in the Alpine (15-min.) quadrangle, the rocks begin to show affinity with the McCutcheon series.

Goldich and Seward (1948, p. 14) divided the Buck Hill series into six formations named, from oldest to youngest, Pruett formation, Cottonwood Spring basalt, Duff formation, Mitchell Mesa rhyolite, Tascotal formation, and Rawls basalt. The writer uses essentially the same divisions as employed by Goldich and Seward, except that the "intercalated" flows in their Pruett formation are treated as separate formations, and the name "Pruett"

is restricted to the tuff, sandstone, conglomerate, and limestone below the Crossen trachyte. The thin weathered tuff members separating the flows are included with the underlying flow in each formation. The name for the Mitchell Mesa "rhyolite" is changed to Mitchell Mesa welded tuff.

Pruett tuff.—Goldich and Elms (1949, p. 1145) described the Pruett formation as "...principally volcanic tuff but includes conglomerate, tuffaceous sandstone and breccia, and tuffaceous fresh-water limestones. Interfingering with the tuff are flows of trachyte, basalt and andesite." To the "intercalated" flows they gave the names Crossen trachyte, Sheep Canyon basalt, and Potato Hill andesite. They believed that deposition of the tuff and related sediments was locally interrupted by invasions of lava from the north. This conclusion is a logical interpretation of relations south and southwest of the Cathedral Mountain quadrangle (where, for example, the Cottonwood Spring basalt rests on lower Pruett tuff in the Buck Hill quadrangle but is missing in Tascotal Mesa quadrangle). But to the north in the Cathedral Mountain and Alpine (15-min.) quadrangles the flows are continuous and very extensive, not local intercalations. The flow units are separated from one another by erosional unconformities; for example, the Sheep Canyon basalt poured out on a hill-and valley topography developed on Crossen trachyte, with the valleys cut through the trachyte and into the underlying tuff. The layers of tuff separating the lavas show considerable weathering, and in places much of this "tuff" is a product of decomposition of the underlying lava. The Pruett tuff, as interpreted by the writer, represented a time of dominant tuff deposition ending with the beginning of Crossen trachyte flows; Crossen time ended after a long period of erosion with the outpouring of the first of the Sheep Canyon flows; and so on. For these reasons, the Crossen trachyte, Sheep Canyon basalt, and Potato Hill andesite are treated as formations, and the name Pruett tuff is restricted.

The Pruett tuff is exposed in the slope of the generally east-facing escarpment which extends from the central part of the southern boundary, along the east margin of Crossen Mesa, in a northeasterly direction to Mt. Ord, in the northeast corner of the mapped area. It has been traced northward along the scarp forming the eastern boundary of the Tertiary volcanic rocks to the northeast corner of the Alpine (15-min.) quadrangle. The formation crops out in the walls and floor of the Mt. Ord basin and in slopes of Elephant Mountain, especially along the east side. The thickest section and one of the best exposures in the area is immediately north of the marble quarry, on the north side of the Cienega Mountain laccolith; smaller areas outcrop around the base of Cienega Mountain on the northwest, west, and south sides. About 300 feet of Pruett tuff is exposed immediately east of the McIntyre Peak intrusion.

This nonresistant basal formation capped by more resistant lavas crops out in fairly steep slopes with more or less concave profiles littered with talus or covered with colluvium. No complete section can be seen at any single locality. The base and upper part are exposed only in a few places.

The Pruett tuff averages 597 feet thick between the Pruett ranch in Buck Hill quadrangle and the northeast corner of the Alpine (15-min.) quadrangle (a north-south distance of about 35 miles); the minimum thickness, at a place in the east-central part of the Alpine (15-min.) quadrangle is 260 feet; the maximum thickness, in the tilted section north of Cienega Mountain, is 798 feet (measured section 1, Pl. 1).

The Pruett tuff consists chiefly of well-indurated, thick-bedded, calcareous, highly altered volcanic glass and fine- to medium-grained tuffaceous sedimentary rocks in various shades of gray, red, green, and speckled combinations, light gray predominating. Some exposures show well-developed stratification. At places beds of incoherent and friable material appear to be nearly pure volcanic ash. Locally, the fine-grained material is silicified. Individual beds are not distinctive and persistent enough to allow correlation between outcrops. The typical tuffaceous beds are composed of a great deal of clay containing mineral and glass particles 0.01 mm–0.07 mm in diameter. Approximately 40 per cent of the average tuff sample has grain size less than 0.015 mm. G. C. Hardin, Jr. (unpublished

manuscript, 1942) identified quartz, orthoclase, plagioclase, olivine, biotite, chlorite, sphene, normal zircon, epidote, magnetite, hematite, limonite, apatite, pyroxene, and sericite. Magnetite, usually partly altered to hematite and limonite, is the principal constituent of the heavy-mineral fraction. Quartz, orthoclase, and biotite are the most obvious minerals in thin sections.

Also included in the formation are conglomeratic tuffaceous sandstone, breccia, and considerable limestone, but these types are more distinctive in the Buck Hill quadrangle.

Most beds in the Pruett are calcareous ranging from slightly calcareous tuff and tuffaceous sandstone to tuffaceous limestone and pure calcitic limestone. Bedding in the limestone ranges from thick to massive. The limestone is dominantly light gray but in some places is darker gray and brown. Some limestone is present wherever a nearly complete section is observable; it occurs at intervals in beds 3–10 feet thick. There are thick accumulations at a few places, particularly in the spur between Sheep Creek and Calamity Creek northeast of Crossen Mesa, in the big re-entrant of the escarpment along the west side of Chalk Valley, and in the Mt. Ord basin.

In the spur between Sheep and Calamity creeks is a sequence of interbedded limestone and calcareous tuff about 300 feet thick; of which the upper 200 feet is light-gray to brown, fine-grained, thick-bedded, fossiliferous, nearly pure calcitic limestone. Beds a few feet thick near the contact with the overlying Sheep Canyon basalt have been mostly replaced by silica. In the big re-entrant of the Mt. Ord scarp, along the west side of Chalk Valley, 55 feet of calcareous tuff and limestone (two 20-foot layers of limestone separated by 15 feet of calcareous tuff) caps the Pruett tuff and is overlain by Sheep Canyon basalt. It is an interesting fact that in these two areas the Crossen trachyte is absent because of pre-Sheep Canyon erosion and the Sheep Canyon basalt rests directly on limestone and tuff which appears to be continuous with the Pruett tuff.

Although the limestone is mapped as Pruett, part or all of it may be post-Crossen. The trachyte was completely breached in these two areas, and erosion may have cut deeply into the underlying Pruett tuff. Such valleys could have contained lakes in which the limestone beds were deposited before the Sheep Canyon basalt covered the surface. Limestone with the same color, texture, and fossil content in beds 3–10 feet thick is common in the tuffaceous layers between flows of the Sheep Canyon basalt. On the other hand, the widespread limestone in unquestioned Pruett tuff also is similar to that in the abnormally thick sections and to the limestone in the Sheep Canyon basalt. Gastropods in the limestone are of no value for correlation. Similarity of lithologic characteristics and fossil content does not rule out a considerable age difference; it does seem to indicate that similar environments were recurrent over a long period of time.

Fairly good exposures in the Mt. Ord basin show several interbeds of limestone in a tuff section capped by Crossen trachyte—wholly Pruett tuff. But there the limestone occurs in beds 3–8 feet thick separated by much thicker tuff layers; the limestone beds appear to be widespread with no local thickening. Chert and fine-grained quartz in irregular-shaped masses and thin stringers are important constituents of the limestone in this area. A typical sample treated with hydrochloric acid yielded a siliceous residue equal to 38 per cent of the original weight. But limestone containing appreciable siliceous material is common in the Pruett tuff.

In the Buck Hill quadrangle, conglomerate composed of well-rounded pebbles of limestone, marble, quartzite, silicified wood, and chert is widespread at the base of the Pruett, but at the few places where the base is exposed in the Cathedral Mountain quadrangle there is little or no conglomerate. Conglomeratic layers do occur at different horizons in some sections; for example, an outcrop on the north side of Cienega Mountain contains two conglomerates; one 278 feet above the base is 48 feet thick, and the other 420 feet above the base is 12 feet thick. In the escarpment on the west side of Chalk Valley, in the upper part of the formation, 50 feet of conglomeratic sandstone containing vertebrate fossils (measured section 13, Pl. 1) is probably equivalent

to the breccia-conglomerate facies that occurs about 60 feet below the top of the Pruett tuff in Buck Hill quadrangle. No conglomerate occurs, however, in an exposure about a mile north of the vertebrate fossil locality, nor in the Mt. Ord basin. The conglomerate beds are lenticular and do not persist for any great distance. Beds observed are composed of well-rounded, poorly sorted, gray, pink, and brown gravel, ranging from granule to cobble in size (mostly pebble), of fine-grained igneous rock, hard silicified tuff, and limestone held together by a medium- to coarse-grained, calcareous, tuffaceous sandstone matrix.

Much fine-grained, thick-bedded to massive tuff is conglomeratic in that it contains harder, more indurated nodules or pellets with the same texture and composition as the matrix. The tuff "gravel" ranges in diameter from a fraction of an inch to about 2 inches, and the shape is somewhat irregular but mostly slightly flattened spherical or elliptical. In some beds these pellets are scattered and constitute a minor part of the rock, but in others they make up a high percentage of the total volume. Because they are harder and more resistant than the matrix, they weather out and litter the slopes. Clifflike exposures show numerous pits originally occupied by the nodules. These nodules may represent mud balls or pellets formed in the air from fine ash emitted as part of moisture-laden, smokelike clouds and deposited as such in a matrix of softer volcanic mud. "Mud pellets" or "volcanic hailstones" have been observed during several volcanic eruptions and are recorded from Triassic and Miocene tuffs and recent ash deposits (Shrock, 1948, p. 331–333).

Tuffaceous, calcareous sandstone is an important constituent of the beds in all parts of the section. It is gray to greenish gray or brown, thin- to thick-bedded, medium- to coarse-grained, and is poorly to well cemented with calcite.

Algal structures, charaphytes, and fossil gastropods and ostracods are abundant. Concentric algal structures make up a large part of the rock. Similar algal limestone occurs in the Huelster formation in the Barrilla Mountains (Eifler, 1951, p. 344).

Several tuff beds around Elephant Mountain contain many internal casts of an unidentified medium-sized (½–1½ inches in diameter), low-coiled land snail; an unidentified, small (¼–¾ inches long), high-spired form is common in association with vertebrate remains in a conglomerate near the top of the Pruett tuff, in the east-facing escarpment along the southeast margin of North Crossen Mesa, 2.28 miles along a bearing N. 26° W. from Nevill's Chalk Valley house at the northeast end of Elephant Mountain. Titanothere remains including fragmentary vertebrae, skull, and jaw fragments (without teeth), and pieces of miscellaneous skeletal parts were taken from this site. The writer also collected vertebrate material from the upper breccia in the Pruett tuff on a small hill west of Cottonwood tank on the O2 Ranch, in northern Buck Hill quadrangle. A well-preserved lower jaw (complete with teeth) of a titanothere, a lower jaw without teeth of a small rhinoceros, and miscellaneous bone and tooth fragments were obtained from the vicinity of Cottonwood tank.

The Pruett tuff rests with angular unconformity on marine Cretaceous rocks, probably on the Boquillas limestone over most of the area. Around Mt. Ord, where the Boquillas was removed by erosion prior to deposition of the tuff, it rests on Buda limestone. Northward from Mt. Ord, to the northeast corner of the Alpine (15-min.) quadrangle, the Pruett overlies Boquillas limestone. On the north and northwest sides of the Cienega Mountain laccolith, it rests on Georgetown limestone; on the south and southwest sides it is in contact with intrusive syenite. It is not known whether the relations seen at the surface represent the true stratigraphic relations in the subsurface in the Cienega Mountain area. Certainly, the discontinuous outcrops on the south and southwest sides are blocks which were torn loose and elevated by intrusion, and possibly the Georgetown limestone was pushed past Gulf beds to a position in contact with the Pruett on the north and northwest limbs during development of the laccolithic structure.

In the Cathedral Mountain quadrangle and the Alpine (15-min.) quadrangle the Pruett tuff is overlain by the Crossen trachyte, except in the Sheep Canyon area and in the

vicinity of the big re-entrant on the Mt. Ord escarpment where the Crossen was eroded away prior to extrusion of the Sheep Canyon basalt, and over the eastern half of Elephant Mountain where it is capped by a syenite sill.

Crossen trachyte.—Goldich and Elms (1949, p. 1151) gave the name Crossen trachyte member to a massive porphyritic trachyte flow capping Crossen Mesa in northern Buck Hill and southern Cathedral Mountain quadrangles and considered it as the lowermost lava in their Pruett formation. This flow has been traced to the northeast corner of the Alpine (15-min.) quadrangle. It forms broad outcrops on Crossen Mesa, North Crossen Mesa, the summit and slopes of Mt. Ord, and over a wide area across the eastern half of the Alpine (15-min.) quadrangle (Fig. 2). Local outcrops occur around Cienega Mountain and McIntyre Peak, where it was arched by intrusive masses and later exposed by erosion.

The unit extends more than 400 square miles, and for this and other reasons the Crossen trachyte should be considered a separate formation.

The description of the Crossen trachyte in Buck Hill quadrangle applies to most of the outcrops of the formation in the Cathedral Mountain quadrangle. It is one of the most distinctive units in the volcanic series and is easily recognized in the field. In the Crossen Mesa area the average thickness is about 150 feet, but it thickens northward, and the average for the Cathedral Mountain and the Alpine (15-min.) quadrangles is approximately 200 feet. The maximum known thickness is at Mt. Ord where 265 feet caps the summit area.

Locally, no trachyte is present, and the Sheep Canyon basalt rests directly on the Pruett tuff. The absence of the trachyte in Elephant Mountain is probably due to pre-Sheep Canyon stream erosion. Inliers, ancient erosional remnants, are exposed in the Sheep Canyon area and in a valley south of Clark ranch headquarters, and an ancient hill-and-valley topography has been exhumed in many places.

Although there are local vesicular zones at different horizons, it appears to be one massive flow. The rock is hard, gives a metallic ring when struck with a hammer, and breaks with an even to subconchoidal fracture. Medium-sized, squarish, glassy phenocrysts of anorthoclase and sanidine are abundant in a fine-grained, reddish-brown groundmass. The weathered rock is nearly everywhere rusty brown; locally it is greenish or various shades of yellow. A distinctive feature of weathered material is the pitted surface which results from weathering out of the feldspar phenocrysts. Local highly weathered areas range from rotten, greenish-yellow, vesicular material to a fine-grained, grayish-yellow, tufflike decomposition product. Perhaps these highly altered materials are remnants of an ancient mantle developed on the trachyte surface.

The flow has well-developed vertical jointing and tends to form nearly vertical cliffs at the edges of mesas and along the escarpment that trends across the east side of the quadrangle. Marginal fragmentation provides abundant scree at the base of the cliffs and over the slope of the underlying Pruett tuff; large talus deposits are especially prominent on the slopes of Mt. Ord.

Vesicular zones in the upper part contain amygdules of chalcedony, some of which are banded with delicate pink, red, and bluish tints and are much prized by agate collectors. Locally, the vesicles are strongly elongated and aligned in a northwestern direction.

The fine-grained, trachytic groundmass consists chiefly of microlites of alkalic feldspar and some altered ferromagnesian material, and finely disseminated hematite gives it a reddish tinge. The squarish feldspar phenocrysts have irregular margins and are principally anorthoclase, with some sanidine. Altered dark-green grains are probably aegerine-augite. Introduced chalcedony is abundant as veinlets and also lines the walls of small cavities in some specimens. All specimens studied from the Cathedral Mountain quadrangle, except two, appear to contain more than 90 per cent alkalic feldspar and little or no primary quartz. Rock from the outcrop on the east side of the McIntyre Peak intrusion contains about 15 per cent primary quartz and must be classed as rhyolite; an inlier south of Clark ranch on State highway No. 118 also

contains an appreciable amount of quartz. Quartz is abundant (5–10 per cent) in samples from several outcrops scattered over the eastern half of the Alpine (15-min.) quadrangle. A chemical analysis of a specimen from Crossen Mesa (Goldich and Elms, 1949, p. 1152) shows a silica content of 71.17 per cent, unusually high for trachyte. The rhyolitic composition of the flow in the McIntyre Peak area is puzzling. There is no doubt that the flow occupies the position of the Crossen. Moreover, the rock looks like typical Crossen trachyte. At Mt. Ord, about 8 miles due east, the rock contains no discernible primary quartz. Unfortunately the area between the outcrops at Mt. Ord and McIntyre Peak is covered by younger flows. In the continuous outcrop from the Mt. Ord area northward across the eastern portion of the Alpine (15-min.) quadrangle no new flow or any suggestion of a facies change is apparent. Yet the flow is rhyolitic in most places north of Mt. Ord.

Sheep Canyon basalt.—The Sheep Canyon basalt overlying the Crossen trachyte is a succession of basaltic lavas separated by thin layers of tuff and limestone (Goldich and Elms, 1949, p. 1153). This formation has wide distribution in the Cathedral Mountain and Alpine (15-min.) quadrangles and, before erosion stripped it off, probably covered much of the country to the south and east. It thins and feathers out southward in northern Buck Hill quadrangle. The thickness gradually increases northward and the greatest known thickness is in an area on the Lane and Decie ranches about 6 miles south of Alpine. The lava was poured out on a very irregular surface, and the number of flows, thickness of individual flows, and the total thickness of the formation vary considerably. A 251-foot section (measured section 4, Pl. 1) contains five flows and four thin tuff and limestone interbeds. (A lava between tuff or limestone partings is considered as a single flow.) If vesicular "tops" were used to distinguish separate flows, it would be possible to recognize several in a given unit, but this method is unreliable. Sections measured at different places over the quadrangle show variation in the number of flows and in total thickness (including tuff and limestone beds) as follows: near the southern boundary on Crossen Mesa, 3 flows, 163 feet; in the Goat Creek and Walnut Draw, 1 flow, 62 feet; North Crossen Mesa, 3 flows, average of 4 sections—190 feet; on Bird ranch west of Ash Creek, 1 flow, 41 feet; on northwest side of Cienega Mountain, 4 flows, 316 feet; in Ash Creek area west of Mt. Ord, 4 flows, 454 feet; in spur between Sheep and Calamity creeks, 5 flows, 251 feet; in Sheep Canyon area, 4 flows, 234 feet.

In Elephant Mountain, complex faulting and lack of good exposures make it difficult to determine the true thickness of the Sheep Canyon formation. Although parts of the unusually thick sections exposed there have been duplicated by normal faults, the actual section appears to be thicker than in the near-by Sheep Canyon and Crossen Mesa areas. A section measured up the west slope, due east of the mouth of Sheep Creek, contains four flows and is 372 feet thick. As the area now occupied by Elephant Mountain was a lowland at the beginning of Sheep Canyon eruptions, the Crossen trachyte having been eroded from the entire area, it is not surprising to find there a thick section of the basaltic lavas of the Sheep Canyon formation.

The greatest accumulation of Sheep Canyon basalt in either the Cathedral Mountain quadrangle or the Alpine (15-min.) quadrangle seems to have been in a basin extending from a point on the west side of Mt. Ord northward to the vicinity of the town of Alpine. West of Mt. Ord, on the west side of Ash Creek, the formation is 454 feet thick. On the Lane and Decie ranches, about 6 miles south of Alpine, a section of undifferentiated Sheep Canyon, Potato Hill, and Cottonwood Spring flows totals 1178 feet, more than 400 feet of which is Sheep Canyon; in a water well drilled on the northern outskirts of Alpine the Sheep Canyon basalt measured 324 feet.

Except for local occurrences of large hypersthene phenocrysts in the first and third flows, all the basalt flows look alike and cannot be distinguished lithologically. All are porphyritic with an even-textured, fine- to medium-grained groundmass. Large, yellowish-orange, greenish, and clear prismatic phenocrysts of labradorite are common but have an erratic distribution. They range in length from a fraction of an inch

to more than 3 inches, with sizes between ½ and 1½ inches predominating.

Many of the vesicular tops are thick and contain much quartz, several varieties of chalcedony, and calcite; high-grade, banded, and moss agate occur in these zones. Also, the vesicles contain much soft greenish material (chlorite?), which gives the zone a distinctive green color. Flow breccias, although not so conspicuous as those in the overlying Potato Hill and Cottonwood Spring flows, are well developed locally.

Slope, drainage, and exposure have greatly influenced weathering of the flows. Spheroidal weathering is especially well developed in gullies, on benches, and on gentle slopes, while platy sheetlike jointing develops on steep, well-drained slopes. Scattered over the surface in areas of spheroidal weathering are many spherical cobbles which represent cores of exfoliated masses. The cobbles weather a dull reddish brown, which is one of the most distinctive features of Sheep Canyon basalt. The color of the fresh break of these cores, a distinctive jet to dark greenish black, is characteristic of all fine- to medium-grained Sheep Canyon flows.

The dominantly feldspathic groundmass has a well-developed diabasic texture. Twinned plagioclase laths (labradorite An_{55}) range from 0.1 mm to about 0.5 mm in length. Labradorite phenocrysts range from a few millimeters to several centimeters in length. Some of the larger plagioclase phenocrysts are zoned, with cores as calcic as An_{60} (Goldich and Elms, 1949, p. 1154). Alkalic feldspar is abundant around the edges of the plagioclase laths and as interstitial filling. Plagioclase and alkalic feldspars make up approximately 70 per cent of the rock. Slightly pleochroic, light purple augite (probably titanaugite) constitutes from 15 to 20 per cent of the rock and occurs in fairly large crystals enclosing feldspar and other minerals. Olivine ($Fo_{70}Fa_{30}$, according to Hardin, 1942) in the form of small subhedral crystals is an important constituent in some of the slides studied, but in most specimens all original olivine is completely altered to antigorite and other decomposition products. Other minerals present are: magnetite, 10–15 per cent; abundant apatite in tiny prismatic crystals; chlorite and antigorite, 5 per cent; some calcite replacing the edges of feldspar laths and in radial clusters; and varying amounts of analcime, zeolites, and clay minerals. Alkalic feldspar is possibly sufficiently abundant to justify calling the rock trachybasalt.

At places between the Crossen trachyte and the first Sheep Canyon flow, everywhere between each flow in the Sheep Canyon succession, and separating the uppermost flow from the overlying Potato Hill andesite are thin layers of altered tufflike basaltic materials or tuff breccia, or limestone, or combinations of these in layers that average about 4.5 feet in thickness, ranging from less than 1 foot to 15 feet. The thickness of the weathered material capping the uppermost flow ranges up to 60 feet, averaging 15 feet. Beds of light-gray to dark-brown, cherty, fossiliferous limestone are common between flows in the southeastern part of the quadrangle. On the west slope of Elephant Mountain, beds of limestone 3–6 feet thick occur between each flow, and a measured section in the Sheep Canyon area (measured section 4, Pl. I) contains one 3-foot bed between the third and fourth flows. The limestone appears to be identical, both in lithology and fossil content, with that found in the Pruett tuff. Where limestone is lacking, as in outcrops in the western and northwestern parts of the mapped area, the thin intervening beds are composed of tuff or tuff breccia, or a zone of tufflike decomposed basalt.

Silicified, gray tuff and tuff breccia, which are fairly common, show phenocrysts and angular fragments of sanidine and quartz in a glassy matrix with more or less well-developed flow structure; several other minerals occur in lesser amounts including magnetite, hematite, limonite, aegerine-augite, riebeckite, sphene, zircon, chalcedony, and calcite. These probably represent rhyolitic tuff indurated by the overlying flow. In places where the interbedded tuff is not so well indurated and silicified it is rusty brown and much altered from ancient weathering but appears to have been originally rhyolitic tuff. Thin sections of tufflike material resting on the uppermost flow show it to be highly decomposed basalt—probably a product of residual weathering. It is reddish brown and

consists of small fragments of basalt containing microlites of plagioclase feldspar in a fine-grained matrix of clay minerals and zeolites.

In most places the Sheep Canyon basalt rests on the eroded surface of Crossen trachyte; but locally it rests on Pruett tuff, in areas from which the trachyte was removed by pre-Sheep Canyon erosion. The unit is overlain by the Potato Hill andesite.

Potato Hill andesite.—Overlying the Sheep Canyon basalt is an andesitic flow and flow breccia designated Potato Hill andesite (Goldich and Elms, 1949, p. 1155). The dark reddish-brown color of the weathered rock together with abundant stubby, glassy plagioclase phenocrysts make this formation easy to recognize throughout the southern half of the quadrangle. It was used as a key bed in mapping the southern area. But there is a gradual facies change northward, and in the northern part of the quadrangle it is a greenish-gray, fine-grained nonporphyritic rock.

Because the lava spread over a highly weathered and somewhat irregular surface of Sheep Canyon basalt and was in turn subjected to a long period of weathering, and because of primary-flow phenomena which may have influenced differential accumulation, the thickness ranges from 35 to 190 feet; the average for 26 measured sections is 79 feet. The minimum thickness (35 feet) is found in the northwest side of North Crossen Mesa; the maximum (190 feet) is in a spur along the west side of Ash Creek between the Clark ranch house and the foreman's house on the Bird ranch. Another area of local thickening is in the upper Sheep Canyon region where the formation is about 100 feet thick. In most outcrops the thickness is 40–90 feet.

Conspicuous, stubby, orange and pinkish, glassy phenocrysts of andesine are abundant in the rock across the southern third of the area but gradually decrease in number northward, finally disappearing in the northern part. The change from highly porphyritic to nonporphyritic can be observed along nearly continuous outcrops. The texture of the groundmass also changes gradually from fine- to medium-grained in the south to very fine-grained in the north. In the field the nonporphyritic facies differs markedly from the porphyritic rock. The very fine-grained nonporphyritic lava weathers greenish gray and develops thin sheet jointing which supplies abundant rectangular chips to the slopes, while the porphyritic facies with its massive flow breccia and thick vesicular zone weathers reddish brown and furnishes irregular blocks and crumbly vesicular material to slopes and benches developed on the outcrops. The vesicular zone contains appreciable amounts of chalcedony (several varieties), calcite, and greenish chloritic (?) material at many places, where it weathers to a greenish color.

Because of the marked change in facies and general appearance of the flow, the stratigraphically equivalent unit in the northern half of the area was not mapped as Potato Hill andesite until study of thin sections of the rocks and comparisons of silica content determined by measuring the index of refraction of fused samples, a technique applied by C. C. Rix (1951, M.A. Thesis, Univ. Texas), seemed to justify such mapping.

Nine representative samples of Potato Hill andesite were taken at well-spaced intervals in a north-south direction across the area; the index of six was 1.555, and of the other three 1.535, 1.545, and 1.565, respectively. Four of the six samples with an index of 1.555 came from the northern nonporphyritic facies and two from the southern porphyritic facies. The sample with an index of 1.535, the northernmost sample used, came from an exposure on the west side of State Highway No. 118 west of Mt. Ord. The sample with the index of 1.565 came from a highly porphyritic zone in an outcrop on Crossen Mesa. According to the index curve worked out by Rix, the silica content for these samples ranges from 51.3 per cent to 64.6 per cent—all within the limits for andesite. The average, 57.4, is very close to the average (57.2) for the diorite-andesite family. The fine-grained nonporphyritic facies has a slightly higher silica content than the porphyritic facies, but this is not unusual. A chemical analysis of a sample of Potato Hill andesite from northern Buck Hill quadrangle shows a silica content of 61.46 per cent (Goldich and Elms, 1949, p. 1156).

The textures range from finely granular to trachytic and glassy. Alteration products,

particularly hematite, hinder resolution of the groundmass, but in granular and trachytic specimens small lathlike crystals of andesine are abundant, and some alkalic feldspar is present in the interstices. Feldspar makes up to 70–85 per cent of the rock. Magnetite and its alteration minerals constitute 5–20 per cent. Other minerals occurring in lesser amounts are olivine, iddingsite, antigorite, biotite, chlorite, zeolites, and clay minerals. One specimen showed basaltic hornblende (about 5 per cent of rock) and one large clear phenocryst of a clinopyroxene with a large extinction angle. Porphyritic facies specimens contain numerous stubby plagioclase phenocrysts which range between 1 mm and 1 cm or more in length. Many of the phenocrysts are rounded and corroded, and some are zoned, ranging from An_{55} in the inner parts to An_{45} in the outer zones (Goldich and Elms, 1949, p. 1156).

A thin section of a red, baked, tufflike material capping the Potato Hill flow in the northern part of the area shows weathered igneous rock fragments up to 0.5 mm in length containing plagioclase microlites, grains and fragments of plagioclase and alkalic feldspar, magnetite, limonite, and chlorite (?) embedded in a matrix of clay minerals and zeolites. This rock is probably a residual decomposition product developed by weathering of the andesite before it was covered by younger flows. The upper surface of the lava shows effects of deep weathering and is overlain in many places by several feet of reddish "residual soil."

Cottonwood Spring basalt.—To a succession of lava flows, ranging from trachyandesite to olivine basalt, resting on Pruett tuff and overlain by the Duff formation in a downfaulted area in northeastern Buck Hill quadrangle, Goldich and Elms (1949, p. 1156) gave the name Cottonwood Spring basalt. Traced northward into the Cathedral Mountain quadrangle, these flows occupy a position between Potato Hill andesite and the Duff formation, a relationship which is maintained across the south-north length of the Alpine (15-min.) quadrangle. Stratigraphic relationships in Buck Hill, Cathedral Mountain, and Alpine (15-min.) quadrangles show that the Cottonwood Spring lavas came from the north and northwest and spread southward over a broad area from which Potato Hill andesite, Sheep Canyon basalts, and Crossen trachyte had been eroded. It may have reached farther south than any of the older flows.

The pre-Duff thickness of the Cottonwood Spring basalt can be determined only in the cuesta infaces on the northwest and west sides of Cienega Mountain—the only places where both the top and bottom of the unit are exposed. Elsewhere, the flows cap hills and highly dissected areas from which the Duff formation has been eroded. The Cottonwood Spring basalt is 286 feet thick in the only complete section measured (northwest limb of Cienega Mountain laccolith). Incomplete sections (erosional remnants) range from a few feet to 332 feet; the maximum occurs east of Goat Creek picnic grounds (may be duplicated by faulting). The average for 24 measured sections, representative of all outcropping areas, is about 150 feet. Between 500 and 700 feet of a 1178-foot section of basaltic lavas exposed on the Lane and Decie ranches, about 6 miles south of Alpine, belong to the Cottonwood Spring basalt. A water well in the City of Alpine penetrated 237 feet of Cottonwood Spring basalt. According to Goldich and Elms (1949, p. 1157) the maximum in northern Buck Hill quadrangle is 325 feet. DeFord (*in* Goldich and Seward, 1948, p. 37) gave a thickness of 220 feet for Cottonwood Spring basalt encountered in Argo Oil Corporation's Mitchell Bros.—State No. 1 (now Gulf Oil Corporation's Mitchell Bros.—State No. 1) located on the southern edge of Whirlwind Mesa in the southwest quarter of the Alpine (30-min.) quadrangle, about 4 miles west of Walnut Draw.

Lack of well-exposed complete sections, the highly weathered condition of the outcrops, the variable number of flows, and the absence of key "beds" make the unit difficult to deal with in the field. It is not possible to correlate definitely any given flow over a sizable area. There may appear to be three flows at one place, while relatively near by there may be six or eight flows in a section of about the same thickness. Vesicular and amygdaloidal zones are numerous, and using these to determine the number of flows would give 15–20 in some

sections, but many of these probably formed as thin lobes or tongues of advancing lava fronts and in turn were capped by several similar fronts before being covered by the main mass of the flow. As well as could be determined, there are four major flows of about equal thickness, but three are seen in most exposures, and many show only two.

In the northern Buck Hill quadrangle and the Cathedral Mountain quadrangle a thin tuff bed is near the middle of the formation, but this tuff cannot be identified with certainty in the northern half of the area. Locally, there are thin layers of tuff and highly weathered basaltic material between flows, but in most outcrops there are no separating tuff beds. Tuff is present between the Potato Hill andesite and the lowermost Cottonwood Spring flow at many places; elsewhere a flow breccia incorporating weathered blocks and cobbles of andesite rests directly on the Potato Hill.

The basalt is dark and fine- to medium-grained in both dense and vesicular phases. Except for rare small glassy plagioclase phenocrysts in small local areas, the flows are nonporphyritic. The many vesicular and amygdaloidal zones contain considerable quartz, chalcedony, and calcite. Much highly prized moss and banded agate comes from vesicular zones and flow breccias in the Cottonwood Spring lavas. Massive coarse flow breccias at different horizons are very conspicuous, and ropy lava is common.

As in the Sheep Canyon lavas, topography and drainage largely control weathering. Well-developed spheroidal weathering occurs in gullies and sheltered areas; platy splitting develops on summits, steeper slopes, and cliffs. The rocks weather dark brown to light greenish gray.

One of the most characteristic features of Cottonwood Spring flows is the speckled schistose appearance of certain units owing to the subparallel arrangement of abundant shiny tabular crystals of plagioclase feldspar. The flaky crystals, 0.5–2.0 mm in diameter and 0.1 mm or less in thickness, have their flat surfaces nearly parallel to the direction of flow. Viewed in cross section, the thin edges present a distinct pilotaxitic texture; they appear as needlelike microlites very close together and nearly parallel.

The rocks range from soda-rich olivine basalt to trachyandesite, with some approaching trachyte. Two textures are found—diabasic for the basalts and bostonitic or trachytoid (irregular laths of feldspar arranged in a divergent subparallel manner) for the more silicic rocks. The finer-grained trachyandesites and "trachytes" possess a trachytoid texture which might be called pilotaxitic. Whether bostonitic or pilotaxitic, the subparallel feldspar laths and/or microlites show well-developed flow structure. Because the rock is so highly weathered, fresh samples are unobtainable; the original ferromagnesian minerals are much altered in most of the thin sections. Twinning is not well developed in most of the plagioclase, and much of the feldspar is characterized by wavy extinction. Orthoclase mantles the plagioclase laths, and alkalic feldspar occurs interstitially even in the basalts. Alkalic feldspar appears to exceed 50 per cent of the feldspar content in some of the more silicic types. Except for the feldspars, all the flows have essentially the same mineral composition. Olivine was originally abundant but is now largely altered to antigorite, iddingsite, and acicular serpentinous minerals which penetrate fractures in the feldspar. Augite, light purple and light green, constitutes 5–10 per cent, and magnetite 10–15 per cent of the rock. Needlelike crystals of apatite are exceedingly abundant in the diabasic rocks. Biotite is rare. Chlorite, calcite, chalcedony, analcime, and zeolites are secondary minerals present in varying amounts. Small patches of chalcedony replace feldspar in some of the rocks with trachytoid and pilotaxitic textures. The basalts contain 75–80 per cent feldspar, about three-fourths of which is labradorite and one-fourth alkalic feldspar. The proportion of alkalic to calcic feldspar in the other rocks appears to range from slightly more than 1:1 to about 3:5.

None of these soda-rich rocks are normal types. Following the usage of Lonsdale (1940), Goldich and Elms (1949, p. 1159) classified analyzed samples of the basal flow of the Cottonwood Spring formation in northern Buck Hill quadrangle as analcime trachybasalt.

Duff formation.—Resting on the weathered

and eroded surface of the Cottonwood Spring basalt in northwestern Buck Hill, most of Jordan Gap, and Cathedral Mountain quadrangles, and on Pruett tuff in northeastern Tascotal Mesa quadrangle is a thick section of rhyolitic tuff containing lenticular beds of sandstone, breccia and conglomerate, and intercalated lava flows. In the southern half of the Cathedral Mountain quadrangle, and in quadrangles to the south and southwest, the formation is predominately thick-bedded, well-indurated, fine-grained rhyolitic tuff with subordinate tuff breccia, tuffaceous sandstone, sandstone, and conglomerate. The tuff is noncalcareous, except in Tascotal Mesa quadrangle where limestone is interbedded (Erickson, 1953, p. 1362). Two or more thin flows of trachybasalt and/or trachyandesite outcrop in southern Cathedral Mountain and Tascotal Mesa quadrangles; flows including trachyte, rhyolite, and basaltic types constitute a major part of the formation in the northern half of the Alpine (30-min.) quadrangle. The formation was named by Goldich and Elms (1949, p. 1159) for Duff Springs in northwestern Buck Hill quadrangle.

Outcrops of the Duff are extensive across the western part of the Cathedral Mountain quadrangle and are especially conspicuous in steep slopes of the east-facing Mitchell Mesa escarpment, Goat Mountain, Cathedral Mountain, and a line of narrow buttes extending northward from Cathedral Mountain. The entire section is exposed on the southeast side of Goat Mountain (measured section 10, Pl. 1) and in the east slope of Cathedral Mountain. The upper part of the formation crops out along major arroyos and numerous fault-line scarps on Mitchell Mesa; the lower beds cap the tilted volcanic sequence on the northwest side of Cienega Mountain laccolith. It is exposed over a wide belt extending northward from the Cienega Mountain syenite mass around Cathedral Mountain and northeastward along either side of Calamity Creek into the Alpine (15-min.) quadrangle. Alluvium covers the formation in the northwestern part of the area mapped. Acidic lavas (Decie member, Tdd on geologic map, Pl. 1) first appear as thin tongues near Haley Mountain and McIntyre Peak and increase in thickness very rapidly toward the north.

Thicknesses of the Duff formation are: 764 feet at Needle Peak in Tascotal Mesa quadrangle (Erickson, 1953, p. 1363); 1015 feet near Duff Springs in Buck Hill quadrangle (Goldich and Elms, 1949, p. 1160); 1500 feet in Argo Oil Corporation's Mitchell Bros.—State No. 1 in the southwest quarter of Alpine (30-min.) quadrangle (DeFord, *in* Goldich and Seward, 1948, p. 37); 1399 feet on southeast side of Goat Mountain; and more than 1500 feet west of McIntyre Peak. The maximum thickness will probably be found to the northwest, in the Paisano Peak quadrangle.

The tuff is chiefly fine-grained rhyolitic glass in various stages of alteration and contains scattered grains of feldspar and quartz and flakes of biotite. Most of the tuff is thick-bedded and well stratified, but some is massive; thinly laminated zones are present, and some is cross-bedded. The tuff is largely light gray—which appears glaring white in the brilliant west Texas sunlight; other colors include buff, brown, pink, and red. Small white chalky fragments, possibly kaolinized feldspar grains, in the fine-grained light gray matrix gives much of the tuff a speckled appearance. Many weathered slopes are strewn with small rounded tuff pellets and pebbles. Rounded nodules that make up an important part of some tuff beds may have been mud pellets from smoke-like clouds deposited along with the enclosing fine ash.

Many lenticular, stream-channel, and flood-plain deposits, ranging from tuffaceous sandstone to boulder conglomerate, are in the lower and upper parts of the formation. On the southeast side of Goat Mountain there are five sandstone-breccia-conglomerate beds 3–25 feet thick within the lower 214 feet of the section; the upper zone, 90 feet thick, is 240 feet below the top and appears to be more persistent than the lower beds. That these coarse-grained lenticular beds are stream-laid deposits is clearly shown by the poor sorting, rapid facies changes, scour-and-fill relations, and cross-bedding. The particles in the breccia and the conglomerate are syenite, trachyte, rhyolite, epidote rock, scoria, vesicular and dense basalt and andesite, and tuff. Many of the rocks probably originated in the Duff formation to the north; some could be from older flows in the Buck Hill succession, but others, for example

the syenite and epidote rock, are not known in any contemporaneous or older formations in the area. Exposed syenite intrusions are younger than the Duff and could not have supplied gravel to its conglomerate members; therefore, either pre-Duff or contemporaneous intrusions must have been first eroded and then covered by younger effusive rocks.

Resistant clastic dikes of fine-grained tuff, 3-6 inches wide, are well developed in tuff beds at the head of Walnut Draw and in the southeast slope of Goat Mountain; some are traceable for more than 50 yards. Many show slickensides and brecciated surfaces, suggesting that they developed along joints as a result of small movements effected by major faulting near by. There are more or less complementary sets—one striking N. 70° W., the other N. 15° E.

The approximate boundary between distinctly southern and northern facies in the Duff formation lies in the latitude of Cathedral Mountain. To the south it is chiefly tuff with some sandstone, breccia and conglomerate, and thin basaltic lava flows. Flows increase in number, thickness, and kind to the north, and in the area southwest and west of the town of Alpine make up a large part of the formation. The Duff lava increases from about 150 feet thick in the east slope of Cathedral Mountain to more than 700 feet thick in the area west of McIntyre Peak.

The flows exposed in the east slope of Cathedral Mountain and southeast slope of Goat Mountain are olivine trachybasalt. Two flows are well exposed at Goat Mountain—one 10 feet thick and the other 40 feet thick are 330 and 800 feet below the top of the formation, respectively. The first unit has been highly affected by analcimization and zeolitization. Weathered zones contain much analcime as small euhedral crystals and crystal aggregates in cavities, cracks, and fissures, and especially along horizontal planes between thin sheets of basalt separated by weathering processes. It is most abundant and appears to be forming in moist areas where there is seepage along the sheetlike jointing planes. Some of the analcime is clear, but most is veneered with green opaque material, probably a mineral of the chlorite group. Long prismatic crystals of natrolite and fibrous radiating crystals of thomsonite—the two commonly intergrown and penetrating clear calcite crystals—are common in amygdaloidal cavities and veins in association with unidentified zeolites and abundant calcite. Solutions causing the analcimization and zeolitization probably came up along the Walnut Draw fault and spread into the Duff lava flows.

Thin sections show that the two flows are much alike, except for degree of secondary alteration. The primary minerals are more severely attacked by analcime and zeolites in the lower unit. The texture of the groundmass is between diabasic and trachytic. Labradorite laths and phenocrysts are mantled with alkalic feldspar; the ratio of calcic feldspar to alkalic feldspar is about 3:1. Before alteration, the total feldspar content was 65–70 per cent of the rock. Olivine and its alteration products, iddingsite, antigorite, and chlorite, account for 10–15 per cent of the volume (nearly all the olivine has been altered). Augite and magnetite each make up about 5 per cent, and apatite in the form of slender needles is an important accessory. Analcime, zeolites, and calcite are abundant secondary minerals. In the lower flow, analcime and zeolites have largely replaced feldspar and other minerals and constitute as much as 20 per cent of the rock.

DECIE MEMBER: The northern facies of the Duff differs from the southern facies in that the effusive rocks are predominantly rhyolite, trachyte, and trachyandesite, whereas flows in the southern part are chiefly trachybasalts. A succession which appears to constitute more than half the Duff formation in the Paisano Peak quadrangle, is designated the Decie member (Tdd on map, Pl. 1), named for exposures on the Decie ranch near McIntyre Peak in Cathedral Mountain quadrangle. These flows moved in from the north and northwest; the southernmost tongue, a trachyte porphyry that reached a point west of Haley Mountain, is about 60 feet above the base of the Duff and is 60–110 feet thick west of Haley Mountain and along the west side of the McIntyre Peak intrusive mass. A second tongue, a rhyolite porphyry, crops out around the east and north sides of McIntyre Peak. Deformation around the McIntyre Peak intrusive

mass prevents determination of exact stratigraphic relations, but the base of the rhyolite appears to be approximately 150 feet above the base of the Duff with a maximum thickness of 237 feet. A few miles north and northwest of McIntyre Peak the Decie is a thick succession of flows of rhyolite, trachyte, trachyandesite, and massive flow breccias.

The rock comprising the lower trachyte flow is a fine- to medium-grained porphyry with many glassy phenocrysts of albite. The fresh rock is yellowish brown and the weathered lava is light chocolate brown. Thin sections reveal a fine granular groundmass, 75–85 per cent alkalic feldspar, enclosing numerous albite phenocrysts of various sizes and shapes—squarish, rectangular, lath-like, and irregular, some more than 5 mm long. Magnetite and its alteration products, limonite and hematite, constitute 1 per cent; pale lead-gray augite, 2 per cent; light-brown sodic hornblende, possibly kataphorite, 2 per cent; and light dark-brown biotite, 2 per cent; olivine (mostly altered) and its alteration products, iddingsite, bright-green chlorite (?), and antigorite, 10–15 per cent; apatite is an important accessory. The rock is an olivine trachyte porphyry.

The upper flow is a fine-grained, grayish-pink porphyritic rhyolite. Thin sections show a spherulitic-trachytic groundmass composed largely of feldspar microlites and interstitial quartz enclosing many square phenocrysts of anorthoclase, many of which show well-developed quadrille structure. The constituent minerals and their estimated percentages are: feldspar, 70 per cent; quartz, 15 per cent; magnetite and limonite, 4 per cent; iddingsite and chlorite, 5 per cent; apatite, trace; riebeckite, traces in patches of altered iron oxide.

Mitchell Mesa welded tuff.—Goldich and Elms (1949, p. 1161) named the thin cap rock of Mitchell Mesa in northwestern Buck Hill quadrangle the Mitchell Mesa rhyolite. This rock is similar to "ignimbrite" and "welded tuff" described by Marshall (1935), Mansfield and Ross (1935), Gilbert (1938), and others.

Following Fenner (1948, p. 883), Erickson (1953, p. 1376) described the Mitchell Mesa "rhyolite" as a "tuff-flow". Fenner differentiated "welded tuff" and "tuff-flow" on the basis of the degree of "welding".

Perhaps a name that indicates the degree of welding is desirable, but the method of emplacement of such deposits opposes use of the term "flow". *Nuées ardentes* is a suitable name for the "flowing" material. Presumably, there is no mass flowage once the material has been deposited, so that the term "ignimbrite", or preferably "welded tuff", would best apply to deposits of *nuée ardente* origin.

From 30 to 60 feet of the Mitchell Mesa welded tuff forms a resistant cap rock over all of Mitchell Mesa, except where it is breached by streams and many normal faults. It is well exposed in escarpments bounding the mesa on all sides and along arroyos and in fault-line scarps on top. Not restricted to Mitchell Mesa, it forms a well-developed bench about 700 feet above the base of each mountain in Goat and Cathedral mountains. The formation also caps and forms cliffs around three narrow buttes extending in a line northwestward from Cathedral Mountain to a point west of McIntyre Peak—the northernmost known outcrop.

In addition to outcrops in Buck Hill, Jordan Gap, and Cathedral Mountain quadrangles, and the southwest quarter of the Alpine (30-min.) quadrangle, the formation crops out over about 35 square miles on Bandera Mesa in Tascotal Mesa quadrangle (Erickson, 1953, p. 1364) and a sizable area occurs near the town of Shafter in Shafter quadrangle (Rix, C. C., 1953, Ph.D. dissertation, Univ. Texas); it caps small outliers near Fresno mine on the southwest side of the Solitario dome in Terlingua quadrangle, and similar rock is reported in Agua Fria quadrangle (Moon, 1953).

The thickness is uniform over a wide area. From Bandera Mesa in the south to the northernmost exposure in the Cathedral Mountain quadrangle it forms the cap rock on mesas, buttes, and other erosional remnants that averages 60 feet thick—ranging from 28 to 75 feet. Where it is overlain by the Tascotal tuff and exposed in cliffs in the sides of Goat and Cathedral mountains, it is 58–134 feet thick, averaging about 85 feet. Although a swell-and-swale topography tends to develop, the surface undergoing erosion remains nearly level. Columnar jointing is well developed in the rock, and the margins of outcrops are always precipitous.

Lithologically, the Mitchell Mesa welded tuff is the most distinctive unit of the Buck Hill succession. Much of the weathered rock is dark reddish gray but ranges from greasy black to reddish gray. On weathering, small pyramidal quartz and opalescent tabular feldspar phenocrysts stand out from the fine-grained groundmass; in many places the weathered surface is pitted and cavernous. Slightly elongated, vesiclelike cavities scattered through the rock contain soft ashy material, and, locally, fragments of hard "baked" tuff are incorporated in the matrix. Except for a thin layer (up to 2 feet thick) of loose material with the same composition as the welded portion at the bottom, and thin discontinuous areas of similar material on top, the rock is coherent—tough to brittle, and breaks with even to subconchoidal fracture.

The groundmass is composed of shards of pinkish to white, fine-grained rhyolitic glass and its devitrification products, and quartz and alkalic feldspar enclosing phenocrysts of quartz and feldspar. The feldspar (2V = about 35°) is intermediate between sanidine and anorthoclase, but faint quadrille twinning on a few of the phenocrysts suggests closer affinity with anorthoclase. Accessory and secondary minerals, present in minor amounts, include magnetite, zircon, biotite, apatite, hornblende, limonite, hematite, leucoxene, calcite, and chalcedony. Both the quartz and the feldspar phenocrysts have irregular margins due to magmatic resorption; most of the phenocrysts do not exceed 5 mm in length. The glassy groundmass exhibits a vitroclastic "flow" structure.

Tascotal formation.—The Tascotal formation lies on the eroded surface of the Mitchell Mesa welded tuff and is overlain by flows of the Rawls basalt. It was named by Goldich and Seward (1948, p. 21) for Tascotal Mesa in Tascotal Mesa quadrangle where it is represented by approximately 800 feet of tuff, tuffaceous sandstone, breccia, and conglomerate. Erickson (1953, p. 1365–1366) mapped Tascotal Mesa quadrangle and found that the formation contains one basalt flow of small areal extent and lenticular beds of limestone. The formation can be followed continuously from a point 6 miles south of the town of Marfa across southwestern Alpine (30-min.), Jordan Gap, and Tascotal Mesa quadrangles to the northern rim of the Solitario dome, an airline distance of 48 miles.

Except for a few small conical outliers, it has been eroded from Mitchell Mesa. The only important outcrops in the Cathedral Mountain quadrangle are in the steep slopes of Goat and Cathedral mountains, between the Mitchell Mesa welded tuff bench and the Rawls basalt cap. There are four small outliers on the buttes extending northwestward from Cathedral Mountain.

The formation is thickest in the Jordan Gap-Tascotal Mesa area, where it reaches more than 900 feet; the maximum in Cathedral Mountain quadrangle, at the east end of Cathedral Mountain, is 462 feet. The thickness varies considerably within short distances, for example, it is 190 feet near the middle of the south side of Goat Mountain, 280 feet at the west end, and 334 feet at the east end. The average thickness on Goat Mountain is 268 feet as compared with an average of about 370 feet on Cathedral Mountain. It thins rapidly to the north, for in two small outliers capped by Rawls basalt on the butte west of McIntyre Peak, the northernmost outcrop, it is only 50 feet.

The formation is composed of light-gray and yellow sandy tuff, coarse sandstone, and pebble conglomerate. The pebbles are basalt, trachyandesite, and fine-grained syenite. Along the upper contact is a zone, 1–2 feet thick, of pink to red, fine-grained, baked tuff. The best outcrop in the area is at the east end of Cathedral Mountain in a nearly vertical cliff approximately 100 feet high. This exposure shows thick beds of yellow tuff and tuff breccia containing large angular blocks of basalt and conglomerate. Outliers on the buttes northwest of Cathedral Mountain contain light-gray, medium-grained, compact tuff, coarse to very coarse sandstone composed of clear grains of quartz, many of which are small pyramidal crystals, and pebble conglomerate cemented with a mixture of coarse sand and tuff. A zone of pinkish baked tuff beneath the upper contact is very hard and breaks with a conchoidal fracture.

Rawls basalt.—The youngest formation in

the Buck Hill series, a succession of interfingering flows of trachybasalt and trachyandesite, with interbeds of tuff, tuff breccia, sandstone, and conglomerate, overlying the Tascotal formation, was named the Rawls basalt for the Rawls ranch on Tascotal Mesa by Goldich and Seward (1948, p. 22). It is extensive in southwestern Tascotal Mesa quadrangle, where it attains a thickness of 937 feet on LaMota Mountain (Erickson, 1953, p. 1369), and it extends into Polvo, Shafter, and Marfa quadrangles.

In the Cathedral Mountain quadrangle, the Rawls basalt has the same general distribution as the Tascotal formation—in small outliers on Mitchell Mesa and on a butte west of McIntyre Peak and over the summit areas of Goat and Cathedral mountains. The average thickness on Goat Mountain is about 270 feet, ranging from 150 to 370 feet, and on Cathedral Mountain, about 450 feet, ranging from 380 to 545 feet. On two small outliers on the butte west of McIntyre Peak, the northernmost exposure, the thickness is 30 and 75 feet respectively. The erosional remnants on Goat and Cathedral mountains are considerably thicker than on adjacent, structurally lower Mitchell Mesa and buttes. Also, the underlying Tascotal formation is thicker on these mountains than on the mesa and buttes.

The thicker sections on the mountains are made up of at least two flows of trachybasalt, each of which contains zones of coarse flow breccia. There are no tuff, sandstone, or conglomerate interbeds. The lower flow is very fine-grained, nonporphyritic, grayish-black basalt; the upper lava capping the highest summits on Goat Mountain is similar to the lower rock but is slightly coarser grained and porphyritic. The massive flow breccias are composed of an agglomeration of angular fragments, ranging from a fraction of an inch to more than 3 feet in diameter, "welded" into very coherent and resistant masses. The flow-breccia zones contain much black chalcedony in the form of botryoidal lining in cavities and coatings around blocks and in veins and stringers interlacing the breccia. Many cavities in the rock are lined with drusy quartz.

The lower lava is composed of a matte of tiny labradorite laths, mantled with alkalic feldspar, in well-developed flow alignment. The alkalic to calcic feldspar ratio is about 1:1, and feldspar accounts for 75–80 per cent of the volume. Magnetite-limonite and iddingsite (after olivine) each constitutes about 5 per cent of the rock. Interstitial to the feldspar, in a pattern similar to augite in other basalts in the area, are many small grains of slightly pleochroic, yellow to reddish-brown pyroxene (?) which has high relief, moderate birefringence, high dispersion, negative elongation, and a small extinction angle. Other minerals present in minor amounts include apatite, chlorite, antigorite, leucoxene, and analcime.

The upper basalt is diabasic and porphyritic and contains many small prismatic and irregularly embayed phenocrysts of labradorite mantled with alkalic feldspar. Approximate alkalic to calcic feldspar ratio is difficult to determine because the feldspars are so severely attacked by analcime and zeolites. The original feldspar content was probably 60–70 per cent of the rock, but analcime and zeolites have replaced feldspar to make up about 20 per cent of the volume. Slightly pleochroic augite and magnetite-ilmenite each account for approximately 10 per cent. Olivine, originally about 5 per cent of the rock, has been completely altered, principally to iddingsite. A green chloritic (?) mineral forming a coating around analcime and patches of zeolites is fairly abundant; secondary calcite is common.

Age and correlation.—The writer has established an Eocene age for the Pruett tuff by vertebrate fossils collected from localities in the Cathedral Mountain quadrangle and in the northern Buck Hill quadrangle. Material obtained in 1951 from a breccia-conglomerate 60 feet below the top of the Pruett tuff on a small hill near Cottonwood tank on the 02 Ranch in northern Buck Hill quadrangle (Goldich and Seward, 1948, Stop 5, p. 30) was studied by John A. Wilson, The University of Texas, who stated:

"The titanothere lower jaw from the Cottonwood tank locality agrees very closely in evolutionary development with a specimen in the collections of the Bureau of Economic Geology of The University of Texas from the lower part of the Vieja series near Porvenir, Presidio County, Texas."

Stovall (1948) described a suite of fossil vertebrates including titanothere collected

from tuff beds beneath the quartz pantellerite rim rock, in the lower part of the Vieja series (Vaughan, 1900), near Porvenir—the same beds from which the titanothere specimen in the collections of the Bureau of Economic Geology was obtained. Stovall assigned the assemblage a Chadron (lowermost Oligocene) age. In 1946, collections containing a large mammalian fauna were made from the same tuff unit by Bryan Patterson and James H. Quinn of the Chicago Natural History Museum. Patterson considered the fauna equivalent to that of the Chadron formation (Goldich and Elms, 1949, p. 1144). John A. Wilson noted:

"This fauna was identified as Duchesnean (oral communication) by Patterson. There has been controversy as to the age of the Duchesnean, but at a meeting of the stratigraphic committee in Boston, 1952, it was placed in the upper Eocene. Therefore, it seems safe to assume that, on present evidence, the Pruett tuff (lower part of the Pruett formation as defined by Goldich and Elms) and the lower part of the Vieja series are about the same age—Duchesnean or uppermost Eocene."

Vertebrate fossils indicate that the Pruett tuff (restricted) is approximately the same age as the Huelster formation of the McCutcheon volcanic series in the Barrilla Mountains and the lowermost tuff beds in the Vieja series in western Presidio County, Texas. A rhinoceros tooth collected by Baker (1935, p. 151) from tuff beds within 200 feet of the base of the McCutcheon series (Huelster formation), on the Casey ranch 11 miles east of Balmorhea, was identified by R. A. Stirton as *Hyracodon*. Remains of this genus were also obtained from the lower tuff beds in the Vieja series.

Using fossil plants, Berry (1919, p. 1–9) assigned an early Eocene or Paleocene age to what is now known as the Huelster formation, but the *Hyracodon*, a more reliable index, indicates later Eocene.

Following eruption of the Crossen trachyte there was a long period of erosion which produced a hill-and-valley topography on the trachyte surface; in a few places valleys were cut through into the underlying Pruett tuff. The top of the Eocene is placed at this important unconformity.

Overlying the tuff from which vertebrates were collected in the Vieja series is an acidic flow, similar to the Crossen trachyte, described by E. C. E. Lord (1900, p. 90–95) as quartz pantellerite. Possibly the Crossen trachyte and the quartz pantellerite (Rim Rock) are equivalent in age. Overlying the Huelster formation in the McCutcheon series is a succession of acidic flows named the Star Mountain rhyolite by Eifler (1951, p. 345). The Crossen trachyte is possibly equivalent to the lower part of the Star Mountain rhyolite.

The top of the Eocene is arbitrarily placed at the top of the Crossen trachyte, and, although no fossils reliable for age determination have been found in the succession above the Pruett tuff (restricted), the volcanic rocks above the Crossen trachyte are shown (Pl. 1) as Oligocene and younger (?).

A period of dominantly acidic volcanism ended with eruption of the Crossen trachyte. The next outpourings produced basalts, trachybasalts, and trachyandesites which make up the Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt. Thin layers of limestone and/or tuff separate flows of Sheep Canyon basalt. At the top of the Sheep Canyon basalt and the Potato Hill andesite are thick weathered remnants of tuff-like decomposed lava produced by weathering. Much Cottonwood Spring basalt was removed by erosion before it was covered by the Duff formation. At least three limestone interbeds and deeply weathered, eroded surfaces in this group indicate a long time—perhaps all of the Oligocene. The Sheep Canyon basalt-Potato Hill andesite-Cottonwood Spring basalt succession is possibly equivalent to the upper two-thirds of the Star Mountain rhyolite in the Barrilla Mountains.

Goldich and Elms (1949, p. 1143–1146) tentatively assigned their Pruett formation (which included Pruett tuff, Crossen trachyte, Sheep Canyon basalt, and Potato Hill andesite) to the Eocene. This was based on the gastropod *Goniobasis tenera carterii* (?) which is abundant in limestone lentils in the Pruett tuff and Sheep Canyon basalt. But the stratigraphic ranges of Tertiary nonmarine and terrestrial gastropods are not well enough established for reliable correlation and close age determination.

After a long period of erosion which removed much of the Cottonwood Spring unit, a new volcanic cycle produced the enormous quantity of rhyolitic pyroclastic material found in the Duff formation, Mitchell Mesa welded tuff.

and Tascotal formation. Many lenticular stream deposits and lentils of nonmarine limestone at different horizons in the Duff and Tascotal formations show that the eruptions were intermittent over a long period of time. Possibly this group is Miocene.

The Duff formation was assigned to the Oligocene and correlated with lower Vieja tuff beds by Goldich and Elms (1949, p. 1144–1145) largely on the basis of a small gastropod associated with *"Helix" hesperarche* at Church Mountain and other places in Jordan Gap quadrangle. It was thought to be the same species, *Mesodon* (*"Helix"*) *leidyi* (Hall and Meek), as that found with vertebrates in tuff of the lower Vieja series. Since it occurs in both Eocene and Miocene beds (Henderson, 1935, p. 134) this species cannot help differentiate the two units. More recently, vertebrate fossils found in the Pruett tuff have proved that the Pruett tuff (restricted) and the lower tuff of the Vieja series are equivalent. Perhaps the lower part of the Duff formation (Decie member) is equivalent to the Seven Springs formation of the McCutcheon series.

Following deposition of the Tascotal formation, a period of less explosive volcanic activity produced a succession of basaltic, trachybasaltic, and trachyandesitic flows—the Rawls basalt, youngest unit of the Buck Hill volcanic series. Basaltic lavas of Pliocene and Quaternary ages are known in south-central and southwestern New Mexico, and the Rawls basalt may have poured out in late Tertiary time—possibly in early Pliocene. The Buck Hill series probably is in part equivalent to the Square Peak series (Huffington, 1943) in the northern Quitman Mountains in Hudspeth County and to a very thick section known from oil test cuttings near Valentine in Jeff Davis County (Woodward, J. E., 1953, M.A. Thesis, Univ. Texas). The Chinati Mountain series in the Chinati Mountains, Presidio County, may be the same age as the Rawls basalt (Rix, C. C., 1953, Ph.D. dissertation, Univ. Texas). The Square Peak series, approximately 3500 feet thick, rests on Cretaceous sedimentary rocks (upper Washita) and is composed of alternating tuff, basalt, andesite, quartz latite, trachyte, rhyolite, and flow breccia. The more than 6000 feet of lava and pyroclastic material penetrated in the Valentine well resembles the succession found in the Buck Hill and McCutcheon series. The Valentine sequence probably includes equivalents to all Buck Hill units and some younger than the Rawls basalt. The Vieja series exposed in the Tierra Vieja Mountains dips toward the Valentine basin and may represent the basal part of the Valentine succession.

Intrusive Igneous Rocks

General

The total surface area of intrusive rock in the Cathedral Mountain quadrangle is approximately 23 square miles—a little more than a tenth of the area. Individual exposures range from a few square feet to more than 12 square miles. Laccolithic bodies (deroofed trapdoor domes), plugs, sills, dikes, and one volcanic vent are represented. Similar intrusions are even more abundant in the central part of the northern half of the Alpine (30-min.) quadrangle. Except for the volcanic vent, which is made up of vent agglomerate, the intrusive masses are alkalic syenite.

Sills and Dikes

Erosional remnants of thick sills form the cap-rock of Elephant Mountain, the large mesalike mountain in the southeast corner of the quadrangle, and of Haley Mountain in the north-central part. A sill is exposed on the upper slopes of the line of buttes extending northwest of Cathedral Mountain, and the extensive, low outcrops of intrusive rock west and northwest of Cathedral Mountain probably represent sills, the bases of which are not exposed.

Dikes are common and conspicuous in the central part of the northern half of the Alpine (30-min.) quadrangle (around Paisano Peak, Twin Sisters, and Mitre Peak) but not in the Cathedral Mountain quadrangle. Narrow discordant "feeders" occur on the northern sides of Elephant and Haley mountains.

ELEPHANT MOUNTAIN SILL: The sill capping Elephant Mountain covers an area of 4.8 square miles. Its thickness is about 600 feet at the north end, nearly 1100 feet in the middle por-

tion along the west side, and approximately 850 feet at the south end of the mountain. Well-developed columnar jointing aids in the formation of prominent cliffs around the margins. Marginal fragmentation results in thick talus accumulations on the steep slopes below. Two feeders are well exposed on the north side of the mountain, one near the middle and the other at the northeast corner. They are narrow dikelike bodies continuous with the sill, cutting through the underlying layered volcanic rocks and disappearing under the alluvial cover in the valleys at the base of the slope. These feeders were probably from a very large intrusive mass underlying the low area immediately north of the mountain. That such a mass existed is indicated by three small outcrops of syenite in that area, which are probably bosses on the same body. The bosslike nature of one of the outlying outcrops, the one nearest the mountain, is shown by the doming of Pruett tuff beds and Boquillas flags in a small area around the exposed core of syenite. The large buried mass may also extend under the whole mountain because the faulting of the volcanic layers beneath the sill suggests deformation produced by intrusion of an underlying igneous body.

The structural relationship between the sill and the underlying rocks is important to the present topography. Beginning at the westernmost feeder and continuing along the west side and around the south end of the mountain, the sill rests on flows of Sheep Canyon basalt, while eastward from this feeder and along most of the east side it overlies Pruett tuff. The Crossen trachyte is absent, having been removed by erosion before the Sheep Canyon basalt flowed out over the Pruett tuff. The tuff and lava are strongly tilted away from the feeder on the west side. As the upper surface of the sill (present mountain summit) has two general levels, with the highest part over the western half where the sill is underlain by the Sheep Canyon basalt, it appears that the magma came up along a major fissure trending northwest-southeast and spread laterally at two different horizons—northeastward along the Pruett tuff-Sheep Canyon contact, and southwestward along the Sheep Canyon basalt-Potato Hill andesite contact. Emplacement of the thick sill along the Pruett tuff-Sheep Canyon basalt contact elevated the Sheep Canyon basalt and overlying rocks on the northeast side of the feeding fissure, but only Potato Hill andesite and younger rocks were raised on the southwest side. When all overlying rocks were removed by erosion the two-level surface of the sill was exposed. There were probably other feeders to each horizon; the one at the northeast corner of the mountain is continuous with the part of the sill that rests on the Pruett tuff.

HALEY MOUNTAIN SILL: A slightly discordant, tabular mass approximately 300 feet thick is exposed over 0.44 square mile and forms the upper portion of Haley Mountain. The base dips 4° NW. and cuts across Duff tuff and Cottonwood Spring basalt which dip a little more west of north about 3°. The intrusive sheet rests on basal Duff tuff on the east, south, and west and on Cottonwood Spring basalt on the north side of the mountain. A narrow dike cuts obliquely across the underlying volcanic rocks in the north slope. Curved, dikelike prongs enclosing a pocket of Duff and Cottonwood Spring rocks on the west side probably are not true dikes but ridges on the irregular upper surface of the sill.

Haley Mountain is a small erosional remnant with steep slopes on the north, east, and south. The area now covered by the capping sill probably is only a fraction of the original.

SILLS WEST AND NORTHWEST OF CATHEDRAL MOUNTAIN: Tabular sheets apparently spread out in all directions from a feeder exposed in the gap between the first and second buttes northwest of Cathedral Mountain. A southward extension is exposed in the upper slopes on either side of the northern part of the first butte. It intrudes the upper Duff formation discordantly, dipping 4° SE. Northward from the feeder, a more horizontal sheet is well exposed in the upper slopes of the second (middle) butte, in the low area between the second and third buttes and in the upper slopes around the south end of the third butte. It averages 80 feet thick, but both the top and bottom are irregular, and thickness ranges from 50 to 110 feet. This sill is continuous with a low, hilly outcrop of intrusive syenite covering nearly 3 square miles in the flat west of the line of

buttes (mostly on the 101 Ranch). Erosion has exposed the upper surface but not the base; because sill relationships are shown in the slopes of the buttes the entire mass is believed to be a sill. Small isolated knobs sticking up through the alluvial cover are probably local highs of the same sill. An extensive outcrop of intrusive rock with similar surface expression in the same broad flat west of Cathedral Mountain is interpreted as a sill associated with the huge Cienega Mountain intrusion. All these sills cut the upper part of the Duff formation.

Laccolithic Bodies and Plugs

Two deroofed masses of general laccolithic type, the Cienega Mountain and McIntyre Peak intrusions, account for more than half the total outcrop area of intrusive rocks. Of the two, the Cienega Mountain mass comes closer to being a true laccolith, but neither shows completely concordant relations. Part of the Cienega Mountain mass is similar to trapdoor domes described by Knechtel (1944) and Moon (1953), except that faulting is obscured by the intrusion itself. The McIntyre Peak body is more complex, showing features of both a trapdoor dome and a plug.

CIENEGA MOUNTAIN INTRUSION: A continuous outcrop of intrusive rock from Little Cienega Mountain to Cathedral Mountain covers 11.2 square miles. Including isolated exposures near by, the total outcrop area of the Cienega Mountain mass is 12.4 square miles. The major part of the exposed mass forms the large dome-shaped Cienega Mountain. Little Cienega Mountain is a boss on the main body at the southwest corner of the exposed portion, and similar protuberances occur along the southeastern margin of Cienega Mountain. Plugs at the northeast end of Goat Mountain, near the marble quarry on the east and north sides of Cienega Mountain, and lesser exposures west of Cienega Mountain, although not visibly connected, are believed also to be "bumps" on the Cienega Mountain mass. The central part of the Cienega Mountain intrusive mass arched Cretaceous sedimentary beds and layers of Tertiary volcanic rocks on the northwest side of the mountain. Erosional remnants of basal Cretaceous sandstone and conglomerate on the mountain top indicate that the beds dipping off the northwest slope once extended over the summit. Along the base of the west slope the intrusive mass is in contact with steeply tilted Tertiary volcanic rocks. On the south side are small pockets of Cretaceous limestone and Tertiary volcanic rocks dragged up by the intrusion, but the main exposed contact is between the intrusion and slightly tilted volcanic rocks of the upper part of the Tertiary section (Cottonwood Spring basalt)—a relation which holds around the east base of the mountain. The igneous core is in contact with the Duff tuff on the northeast side. Contact relationships present Cienega Mountain proper as an eroded trapdoor dome in which the intrusive core raised the "door" so high that parallel faults on the northeast and southwest sides and the end fault across the southeast side were obscured by the intrusive mass.

The larger mass which includes Cienega Mountain cannot be fitted into the trapdoor dome category. That part exposed around the south side of Cathedral Mountain is beyond the limits of the dome. As was suggested, the wide outcrop west and southwest of Cathedral Mountain may be a sill-like expansion of the body, but exposures immediately south of it are not sill-like. The complex faulting of the volcanic layers in Cathedral Mountain strongly suggests a large irregular intrusion at a shallow depth. The greater Cienega Mountain intrusion must be a complex body with the proportions of a large stock.

MCINTYRE PEAK INTRUSION: McIntyre Peak is a high conical protuberance on a larger mass exposed over 1.5 square miles in the north-central part of the quadrangle. Many plugs, sills, and dikes in the area immediately to the north (southern part of the Alpine (15-min.) quadrangle) and the McIntyre Peak mass may all be parts of one large stock.

An uncovered, modified trapdoor dome adjacent to McIntyre Peak on the east indicates that a sizable portion of the intrusive body extends eastward below the surface. The portion of which McIntyre Peak is a part apparently pushed upward like a plug into overlying Tertiary volcanic rocks, breaking off, tilting, and elevating large blocks of volcanic rock.

The Haley Mountain sill is a remnant of a tabular offshoot from this mass.

EAGLE PEAK VOLCANIC VENT: Several plug-like peaks in the area resemble volcanic necks, but only Eagle Peak can be identified as a volcanic vent. This conical mass of vent agglomerate is only about 300 feet in diameter at the base and approximately 150 feet high and is situated alongside the Calamity Creek fault in the central part of the quadrangle. The rock is a well-cemented, fine-grained volcanic breccia composed of small to medium lapilli of basaltic and andesitic lava and fragments of baked tuff.

Distribution Pattern, Petrography, Relative Age

The intrusive masses in the Davis Mountains show alignment from Elephant Mountain on the southeast approximately N. 25° W. to Sawtooth Mountain and beyond on the northwest. They are especially numerous along either side of a line extending from Cienega Mountain to the northern boundary of the Alpine (30-min.) quadrangle, in an area about 30 miles long and 10 miles wide where larger masses include Cienega Mountain, McIntyre Peak, Ranger Peak, Twin Sisters Peak, Paisano Peak, Twin Mountains, the three Mitre Peak plugs, and Barrillos dome. Several lesser masses occur in the area immediately north of McIntyre Peak and around Twin Sisters Peak. The close spacing of so many masses of mineralogically similar rocks suggests a common source, and perhaps they are all protuberances on one batholithic body underlying the area.

All intrusive igneous rocks exposed in the Cathedral Mountain quadrangle, except the vent agglomerate in Eagle Peak, are alkalic microsyenite. The syenite is remarkably uniform in composition. Except for the dark-green syenite sill on the 101 Ranch, the rock is light greenish gray, fine-grained, and even-textured. It weathers yellowish to reddish brown and breaks down by exfoliation and thin sheet jointing. Rare porphyritic zones contain small phenocrysts of anorthoclase, and flow structure is well developed in the basal parts of some of the sills.

Although thin sections reveal minor variations in mineralogical composition the following description fits the rock generally. The texture is slightly porphyritic, fine-grained, trachytic to granular. Alkalic feldspar constitutes 85–90 per cent of the rock. The feldspars are dusty, extinction in the laths is anomalous, and the twinning is indistinct. There are a few small phenocrysts of anorthoclase. Aegerine-augite is the most abundant mafic mineral, 5–10 per cent. Olivine, an original constituent in all the rocks, is altered completely to serpentine and iddingsite, 1–2 per cent. Apatite is an accessory, and a small amount of analcime is present in most samples. Secondary minerals include limonite, sericite, calcite, clay minerals, and probably zeolites.

Analcime (up to 5 per cent) and calcite are more abundant in samples from Elephant Mountain than in any others. The Cienega Mountain rock contains 1–2 per cent quartz, interstitially and as small grains. The dark-green color of the 101 Ranch sill results from an even distribution of shreds of aegerine-augite in the groundmass (about 10 per cent of the rock).

Noselite (?), enigmatite, and riebeckite were found only in rocks from the McIntyre Peak-Haley Mountain mass and the mass underlying 101 Ranch. Small (up to 1 mm in diameter), dull-white, six-sided crystals of noselite (?) are conspicuous in syenite specimens from these areas. The mineral is isotropic, has an index of refraction of 1.485–1.490, and in nitric acid solution with barium chloride gives a white precipitate of barium sulphate. Most of the crystals are altered to sericite and probably zeolites, and many are rimmed with aegerine-augite and altered riebeckite.

The Elephant Mountain sill is younger than the Sheep Canyon basalt, but how much younger cannot be determined since the beds once above the sill have been removed by erosion. The Tascotal formation is cut by a portion of the Cienega Mountain intrusion; the faults affecting the Rawls basalt on Cathedral Mountain probably resulted from pressures exerted by the mass beneath the mountain. Intrusive rocks in the McIntyre Peak and 101 Ranch areas are younger than the Duff formation. Eagle Peak vent is surrounded by the Cottonwood Spring basalt, but, since it is

on the Calamity Creek fault which cuts the Duff formation, it is probably post-Duff in age. The mineralogical similarity of all the syenitic rocks suggests a genetic relationship and contemporaneous intrusion. In the Cathedral Mountain quadrangle, all the intrusive bodies appear to be younger than the youngest volcanic rocks.

Quaternary System

Local deposits of Quaternary age include talus and colluvium on the slopes and alluvium in the valley flats. Only the alluvium was mapped.

Albritton and Bryan (1939, p. 1423–1474) studied the valley fill in this area and on the basis of disconformities divided it into three formations, from oldest to youngest: (1) Neville, (2) Calamity, and (3) Kokernot. Type localities for these formations are in the Sheep-Calamity Creek valley west and northwest of Elephant Mountain. The formations are well exposed in stream banks and arroyos, but because the valley flats are unterraced the alluvium cannot be differentiated on a geologic map of the scale used.

The alluvium consists of poorly sorted materials ranging from clay and silt to boulders. Basal beds are more coherent and contain much secondary calcium carbonate as white nodules in the silt zones and as an encrustation around pebbles and cobbles in the conglomerates. Upper beds are less calcareous and contain more humic clay. A typical exposure shows 3–4 feet of clay and fine silt at the base overlain by an equal amount of sand and coarse gravel which grades upward into clay and silt containing scattered gravels. In most outcrops the thickness ranges from 10 to 15 feet, but 30 feet is exposed in places and as much as 50 feet has been penetrated in water wells. Conspicuous alluvial fans along tributary streams near the base of steep slopes facing major valleys, built up to a profile of equilibrium during the last period of aggradation, are being dissected at present.

Aquatic and land gastropods occur through all of the fill. Elephant remains have been found only in the lower portion (Neville). Upper beds contain artifacts, hearths, and human burials (Albritton and Bryan, 1939, p. 1172).

Structure

Five diastrophic events are recorded by structural features in the Cathedral Mountain quadrangle. Listed in chronological order these are:

(1) Tilting, uplift, and erosion of the Permian strata prior to the deposition of Comanche beds (post-Capitan, pre-Trinity)
(2) Folding, uplift, and erosion prior to deposition of the Pruett tuff (post-Boquillas, pre-Pruett; post-Cretaceous, pre-upper Eocene)
(3) Gentle tilting of Tertiary volcanic layers (post-Rawls basalt, pre-syenite intrusive activity)
(4) Local doming and faulting caused by intrusion of syenite bodies (post-Rawls, pre-normal faulting and pre-valley-fill; late Tertiary or early Quaternary ?)
(5) Normal faulting (post-syenite intrusive activity and pre-valley-fill; late Tertiary or early Quaternary ?)

That Mt. Ord and the northern Del Norte Mountains stood high at the beginning of Cretaceous deposition, possibly as a low asymmetric ridge connected with the Glass Mountains to the northeast, is shown by the fact that the Comanche Edwards limestone rests directly on the Permian Capitan limestone in that area, while at Cienega Mountain, 13 miles to the southeast, nearly 400 feet of sandstone and conglomerate of Cretaceous (Trinity ?) age underlies the Edwards. Furthermore, the distribution of basal Cretaceous formations in the Del Norte Mountains southward from Mt. Ord show that the Cretaceous sea gradually transgressed high ground in that area. Late Cretaceous, pre-upper Eocene Laramide folding is shown along the eastern margin of the area by the angular unconformity between the Cretaceous strata and the overlying Pruett tuff. South of Mt. Ord the Cretaceous beds dip generally 5°–10° W., but near Mt. Ord the strike changes gradually through 180° of arc around the west side of a domical structure athwart the Del Norte Mountains, and dips are as high as 35°. Strike changes and dip in-

creases similarly along the west side of the broad Altuda dome at the north end of the Del Norte Mountains. Although dipping more gently, 2°–10°, the Tertiary volcanic layers reflect structure of the underlying Cretaceous beds, including the domes at Mt. Ord and Altuda Mountain.

Whereas the strike of the Cretaceous strata exposed along the west side of the Del Norte Mountains is generally north to northwest, the strike of the overlying volcanic rocks is north to northeast. But the strike changes in response to the Mt. Ord and Altuda domes. The gentle regional dip (2°–4°) is to the northwest. Locally, large stock-like intrusions (Cienega Mountain and McIntyre Peak masses) and faults have disturbed the regional trend. The regional dip is slightly altered on the faulted sides of the trapdoor domical portions of the Cienega Mountain and McIntyre Peak stocks, but steep dips extend away for considerable distances on the arched sides. All dips steeper than the average regional dip appear to be related to younger faulting or intrusive action. Since a core of intrusive syenite is exposed in the Altuda dome, the Mt. Ord dome could be the result of a buried laccolithic intrusion. If so, its last deformation may have occurred at about the same time the intrusions in the area were emplaced.

Probably the first folding of the Tertiary volcanic series began when the Duff formation was being deposited and continued through Tascotal time. Beds of coarse conglomerate are abundant in the Duff formation and even more so in the Tascotal formation. All observable intrusions in the area are younger than any of the volcanic rocks, yet conglomerate beds in the Duff formation contain syenite gravel. Perhaps folding was accompanied by intrusive activity. Also, the Tascotal formation where capped by the Rawls basalt on Goat and Cathedral Mountains is much thicker than in Rawls-capped erosional remnants on Mitchell Mesa and the buttes northwest of Cathedral Mountain. The Rawls basalt is considerably thicker on Goat and Cathedral Mountains than elsewhere in the quadrangle, in spite of the fact that both of these mountains have been elevated by faulting and subjected to an increased rate of erosion. A northeastward-trending basin probably existed in the area now occupied by Goat and Cathedral mountains when the Tascotal formation was being deposited and when the Rawls lavas spread over the area. Downwarping initiated in Duff time may have continued through Tascotal time. That the Mitchell Mesa welded tuff between the Duff and Tascotal formations shows no thickening in this area does not preclude the existence of a basin at that time. Being of *nueé ardente* origin, it was probably deposited in a uniform layer over hill and valley alike; no initial dips are apparent in this highly faulted area. But the tilted attitude of the Rawls basalt in Jordan Gap and Tascotal Mesa quadrangles shows that the major folding occurred after Rawls time.

Many normal faults are younger than the regional folding of the Buck Hill volcanic series. Eighteen of the 40 normal faults mapped are associated with igneous intrusions, and 15 occur along the western margin of Mitchell Mesa in the Walnut Draw fault zone. The three major faults, all with downthrow to the southwest, that extend northwest across the southern part of the quadrangle are Calamity Creek, Torvea Canyon, and Walnut Draw faults (Pl. 1).

The Calamity Creek fault enters the quadrangle from the south between Elephant Mountain and Calamity Creek and continues along the east side of the creek for 12½ miles to a point south of Haley Mountain. It strikes nearly north along the west side of Elephant Mountain and to a point northeast of Nevill ranch headquarters, then turns westward and trends N. 25° W. It is concealed by alluvium in Calamity Creek valley at the south end but can be followed easily northwestward from where it emerges from the valley. It crosses State highway No. 118 about 200 yards north of the Calamity Creek bridge, where the Cottonwood Spring basalt on the southwest side has been dropped down against the Crossen trachyte on the northeast. The amount of displacement varies (300–500 feet) along the fault but appears rather uniform as far north as Eagle Peak, from where it dies out rapidly.

The Torvea Canyon fault enters from the south in the southeast corner of the south-central quarter of the quadrangle, strikes

slightly north of west through Torvea Canyon across Crossen Mesa and then follows a sinuous course trending N. 28° W. to a point southwest of Little Cienega Mountain, a distance of about 6 miles. Displacement increases from about 150 feet at the east-facing escarpment of Crossen Mesa to 300–400 feet at the west side of the mesa and then gradually decreases northwestward.

The Walnut Draw fault crossing the southwestern part of the area is the master fault of the Walnut Draw fault zone. It can be traced southeastward across Buck Hill quadrangle and into Santiago Peak quadrangle (Goldich and Elms, 1949, p. 1170). It follows Walnut Draw into the Cathedral Mountain quadrangle and continues N. 15° W. along the east side of Mitchell Mesa and the west end of Goat Mountain. The Walnut Draw fault zone is part of a system of northwest-trending faults developed along the northeast flank, roughly parallel to the axis, of a broad northwest-plunging nose in the Buck Hill volcanic series extending across western Buck Hill and northern Jordan Gap quadrangles (Goldich and Seward, 1948, Fig. 3). The highly faulted eastern margin of Mitchell Mesa lies within the Walnut Draw fault zone.

Displacement along the main Walnut Draw fault is about 450 feet in the southern part of the Cathedral Mountain quadrangle, but the cumulative stratigraphic throw in this area is between 850 and 1000 feet (structure section D-D′, Pl. 1). At the west end of Goat Mountain the vertical separation is 650–700 feet. The main branch faults cutting Mitchell Mesa have a strong northwesterly trend and show displacements ranging from 50 to 200 feet; lesser faults strike in different directions. Several small horsts and grabens are present over the mesa. Minor faulting along the edges of escarpments probably resulted from landslides—toreva-blocks. Both obsequent and resequent fault-line scarps are prominent topographic features in Goat Mountain-Mitchell Mesa area. No actual fault scarps are present in the quadrangle.

Although the faults around Cienega Mountain and McIntyre Peak are obviously associated with intrusive igneous masses, and it is believed that the complex faulting around Cathedral and Elephant Mountains is the result of stresses set up by intrusive bodies beneath them, it is possible that two northwestward-trending faults transecting the lower southwestern slope of Elephant Mountain and two others that cut the northeast end of Goat Mountain are not effects of the local intrusion.

An important fault enters the quadrangle just north of Mitchell Mesa and west of the northwest corner of Goat Mountain (structure section D-D′, Pl. 1). This northeast-striking fault probably extends along the base of the northwest-facing escarpment of Goat Mountain (Pl. 3, fig. 1), but it cannot be traced in the tuff and alluvium. The base of the Rawls basalt on a small hill just outside the mapped area at the northeast corner of Mitchell Mesa is approximately 1150 feet lower than on the southwestern part of Goat Mountain, but 650–700 feet of this displacement was produced by the main Walnut Draw fault.

PHYSIOGRAPHY

The physiography or geomorphology of the Cathedral Mountain quadrangle deserves fuller treatment than can be given to it in a short chapter in a general paper of this kind. The primarily descriptive discussion which follows is designed to do little more than supplement the geologic map (Pl. 1) which lacks a contour base.

The rugged topography includes neck-like igneous peaks, steep cuesta escarpments, fault-line scarps (both obsequent and resequent), mesas and buttes, dissected mountainous divides and isolated rounded hills, dissected pediments and slopes, wide valley flats, and narrow, steep-walled canyons; depositional forms include talus deposits, alluvial fans, and alluviated valley flats.

One of the most prominent landmarks is Elephant Mountain in the extreme southeast corner, a high, somewhat rectangular, mesa-like erosional remnant covering approximately 16 square miles. Its fairly flat summit, about 4.8 square miles in area, stands from 1800 to 2000 feet above the wide valley of Calamity Creek on the west and south and about 1600 feet higher than Chalk Valley on the north. A nearly vertical cliff ranging from about 600

feet to more than 1000 feet bounds the summit and exposes the full thickness of the capping syenite sill. At the base of this escarpment along the west side, a slightly concave bench is well developed on basaltic lavas, and minor benches are developed on interbeds of tuff; faulting across the southwest slope has aided in the development of prominent benches there. The slope developed on the basaltic lavas underlying the cap-rock on the west side has a fairly uniform and steep grade (about 23 per cent). Slopes on the northeast and east sides of the mountain, on the Pruett tuff, are less steep and have a slightly concave profile; the lower portions on the tuff are dissected pediment surfaces. Headward erosion by the major consequent streams has produced several re-entrants in the cap-rock, especially on the east side. Large alluvial fans at the base of the slopes are now being dissected.

Lower mesalike areas—Crossen and North Crossen Mesas—lie across the wide flat valley of Calamity Creek and its tributaries to the west and north of Elephant Mountain. Except for a few scattered outlying low hills of younger lavas, the Crossen trachyte covers these areas, and the gentle northwestward dip of the surface is approximately the dip slope of that lava flow. Consequent (or resequent) streams have cut many shallow valleys into the lava. The relief almost nowhere exceeds 100 feet. Crossen and North Crossen "mesas" are bounded on the south and east by steep escarpments, 300 to 600 feet high (Pl. 3, fig. 2); the flat area ends on the west and northwest as the Crossen trachyte dips under younger volcanic rocks. The escarpment bounding Crossen Mesa on the south and east continues with few breaks from northern Buck Hill quadrangle to and beyond the northern boundary of the Alpine (15-min.) quadrangle; from North Crossen Mesa northward it forms the eastern boundary of the Davis Mountains. This escarpment is an erosional front of a succession of Tertiary volcanic rocks that once extended much farther south and east. The eastern escarpment increases in height toward the north because of structural elevation, standing more than 1000 feet above the valley of Maravillas Creek a short distance south of Mt. Ord. Cretaceous limestones (Boquillas, Buda, and Georgetown) are exposed in the lower part of the scarp in this area.

Mt. Ord, one of the highest summits in the Cathedral Mountain quadrangle (elevation 6850 feet), is a "cuesta" peak capped by Crossen trachyte. Tertiary volcanic layers are bowed around the west side of a large dome, the center of which lies about three-fourths of a mile east-northeast of Mt. Ord in Altuda and Monument Spring quadrangles in the Del Norte Mountains. The Crossen trachyte dips 6°–10° SW., W., and NW. as it bends around the dome. The lava cap breaks off abruptly on the east and northeast sides, surmounting a steep cuesta escarpment overlooking the Del Norte Mountains. Mt. Ord stands about 1800 feet above the bed of Ash Creek at the foot of the dip slope on the west side; the east-facing escarpment is approximately 600 feet high.

Consequent streams flowing down the southwest slope of the Mt. Ord structure cut down through the trachyte flow into Pruett tuff and breached the east-facing escarpment at three places immediately south of Mt. Ord, producing two isolated peaks and a third eminence at the south with steep slopes on the north and east. They also carved an elongated basin south of Mt. Ord and along the west side of the line of peaks.

About 8½ miles west of Mt. Ord are three conical peaks of intrusive syenite, all uncovered plug-like protrusions on the same igneous intrusion. The northernmost and highest, McIntyre Peak (elevation 6350 feet), stands 1200–1300 feet above adjacent stream valleys. An uncovered erosional remnant of a tabular southeastward extension of the same intrusive body now forms the protective cap on Haley Mountain. A buried "hump" on the intrusion produced a trapdoor dome along the east side of McIntyre Peak that presents a steep (18°–22°) generally eastward-dipping slope and a horseshoe-shaped fault scarp, 50–300 feet high, facing southwest, west, and northwest. The Crossen trachyte which forms the surface on this dome dips under younger lavas in a synclinal area to the east. That part of the igneous mass exposed, on which McIntyre and the two other peaks are surmounted, brought up a few large blocks of lava and tuff and left them resting at various angles, es-

pecially around McIntyre Peak. Rugged and highly irregular topography has resulted from erosion of this structurally complex area.

Across Calamity Creek from the McIntyre Peak-Haley Mountain igneous intrusive mass, a broad dissected pediment carved on tuff, sandstone, and conglomerate of the Duff formation rises gently to the base of the steep slopes of Cathedral Mountain and a chain of narrow buttes extending north-northwest from Cathedral Mountain. The great spire of Cathedral Mountain (Pl. 2, figs. 1, 2), an upthrown block of Rawls basalt (elevation 6860 feet), is about 2100 feet higher than the valley of Calamity Creek on the east and stands approximately 1800 feet above the eastern edge of the Marfa Plateau to the northwest. Cathedral Mountain is a rectangular-shaped erosional remnant composed of nearly horizontal layers of alternating tuff and lava which were uplifted and broken by numerous faults caused by the stock-like syenitic intrusion exposed in Cienega Mountain to the south.

The narrow flat-topped erosional remnant projecting north-northwest from Cathedral Mountain is capped by Mitchell Mesa welded tuff, with a few small conical outliers of Tascotal tuff and Rawls basalt. Headward erosion has breached this elongated remnant at two places, forming three separate buttes.

The largest area devoid of appreciable relief in the Cathedral Mountain quadrangle lies west of these buttes. It is the eastern edge of the Marfa Plateau, a broad flat area extending west and northwest to Marfa and beyond. Pediments developed on the Duff formation along the base of the slopes of the buttes on the east, Cathedral Mountain on the southeast, and Goat Mountain and Mitchell Mesa on the south dip under a veneer of alluvium a short distance away from the highlands.

Goat Mountain (Pl. 3, fig. 1) is a high, rectangular, block-like erosional remnant, elongated northeast-southwest, about 3 miles long and 1–1½ miles wide. Like Cathedral Mountain, it is composed of two thick tuffs alternating with two lavas, nearly horizontally disposed. Differential erosion has produced long steep slopes, vertical cliffs, and benches. The southwest and northwest fronts of the mountain are resequent fault-line scarps; the northeast and southeast faces are erosional escarpments. The summit area (elevation 6750 feet) is about 1750 feet above adjacent lowlands on the northwest and southeast and approximately 1400 feet higher than the general level of Mitchell Mesa to the southwest.

East of Goat Mountain and south of Cathedral Mountain, erosion of a complex trapdoor dome has exposed more than 13 square miles of intrusive syenite, the major portion of which (nearly 8 square miles) forms most of broad domical Cienega Mountain. Cretaceous sedimentary beds and Tertiary volcanic layers arched by the intrusion on the west and north have been truncated and shaped by differential erosion into a series of curving cuestas and hogbacks, especially along a northeast trend between Goat and Cathedral Mountains. There are several protuberances on the stock-like intrusion marginal to the Cienega Mountain portion, the most prominent of which is Little Cienega Mountain on the southwest side.

Southwest of Goat Mountain, between the Walnut Draw fault and the western boundary of the mapped area, lies the northeastern portion of Mitchell Mesa. The thick Duff tuff is overlain by a thin, more resistant layer of welded rhyolitic tuff (Mitchell Mesa welded tuff) which forms the cap-rock for the "mesa." This so-called mesa, bounded on the east by an obsequent fault-line scarp parallel to the Walnut Draw fault, is broken by many normal faults, most of which strike northwest, with small displacement—some downthrown to the northeast, others to the southwest. The height of the scarp is about 250 feet at the north end, 500 feet along the middle stretch, 800 feet overlooking Walnut Draw, and approximately 650 feet at the southern boundary of the quadrangle. Several small landslide blocks occur along the edge of the escarpment.

South of Goat Mountain, between the graben occupied by Walnut Draw and Goat Creek, a rough well-dissected terrain developed largely on the Cottonwood Spring basalt slopes gently

PLATE 2.—VIEWS OF CATHEDRAL MOUNTAIN

FIGURE 1.—Rawls basalt, spire and upper bench of Cathedral Mountain. View northeastward
FIGURE 2.—Cathedral Mountain. View southwestward from the Brown ranch

FIGURE 1

FIGURE 2

VIEWS OF CATHEDRAL MOUNTAIN

FIGURE 1

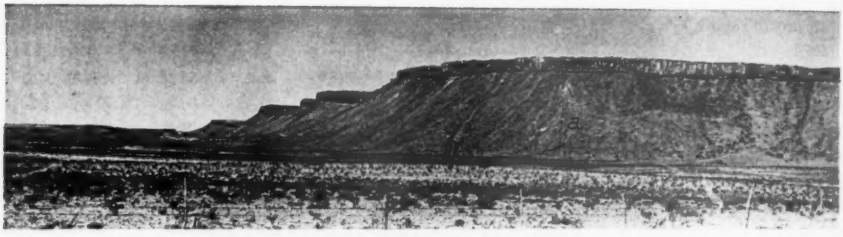

FIGURE 2

FIGURE 3

toward Goat Creek. Goat Creek and its tributaries from the west flow against the dip of the volcanic layers and have carved steep-walled narrow valleys and gorges separated by high, hilly divides. Between the northern edge of this dissected basaltic surface and the steep slope of the southeast escarpment of Goat Mountain is a wide dissected pediment cut on the Duff formation. Its gently sloping surface is indented by numerous gullies and shallow valleys, and there are a few low ridges and isolated hills of more resistant rock, but on the whole there is little relief.

Starting immediately south of Little Cienega Mountain and continuing southward into northern Buck Hill quadrangle, an irregular mountainous trend of dissected ridges and buttelike summits composed of lavas and tuffs forms the drainage divide between Goat and Calamity Creeks. A similar northwest-trending mountainous area divides the drainage between Sheep and Calamity Creeks. These mountainous divides are the western and northern boundaries of Crossen Mesa. From the mouth of Ash Creek northwestward for about 5 miles and then northeastward to the latitude of Mt. Ord, a narrow chain of hills and ridges carved largely on basaltic lavas forms the divide between Calamity and Ash Creeks.

More than 70 per cent of the Cathedral Mountain quadrangle is drained by Calamity Creek and its tributaries, Sheep and Ash creeks; about 25 per cent is drained by Goat Creek. The flat area in the northeast corner (Marfa Plateau) and a part of Mitchell Mesa drain westward into Alamito Creek. Drainage off the steep east-facing Davis Mountains escarpment between Mt. Ord and Elephant Mountain goes via Chalk Valley to Maravillas Creek which flows southeastward across the Del Norte Mountains and the Marathon basin. Extending northwestward from Mt. Ord is an important drainage divide. North of this divide, waters flow northeastward to the Pecos River, and south of it to the Rio Grande. Except for short spring-fed reaches, all streams are intermittent. The longest stretch of permanently flowing water is in Calamity Creek—from the vicinity of Haley Mountain southward to a point west of Elephant Mountain, where the water disappears into the valley fill. Goat Creek carries a trickle of water supplied by seepage springs, and, except during periods of drought, some water is usually present along short stretches in both Sheep and Ash Creeks. Sparse vegetation, a well-developed drainage network with steep gradients, a thin rocky soil mantle, and bare rock surfaces all facilitate rapid run-off. Dry creeks become torrential almost immediately after a heavy rain but diminish within a few hours.

Although the regional dip of the Tertiary volcanic rocks is west and northwest, the master drainage is southward. Most of the tributaries are consequent (or resequent) and form radial or dendritic patterns according to the structure and topography. Ash Creek appears to be a subsequent stream developed almost parallel to the strike of the volcanic layers along the west side of the Mt. Ord structure. Escarpment fronts are scalloped by short obsequent streams. As obsequent streams, Sheep and Torvea creeks have cut far into the escarpment bounding Crossen Mesa. The cross-dip flow of Walnut Draw is due to a graben with increasing displacement toward the southeast. Goat Creek has carved a narrow, steep-walled gorge across southern Crossen Mesa in northern Buck Hill quadrangle, diametrically opposed to the dip of the volcanic rocks. Calamity Creek also flows in a direction opposite to that of the rock inclination, but no canyon or gorge developed where it crosses the eastern escarpment of the Davis Mountains because of the Calamity

PLATE 3.—STRATIGRAPHY, STRUCTURE, AND TOPOGRAPHY

FIGURE 1.—Northwest-facing escarpment of Goat Mountain—(a) Duff tuff, (b) Mitchell Mesa welded tuff, (c) Tascotal tuff, and (d) Rawls basalt

FIGURE 2.—Escarpment bounding Crossen Mesa, northwestward view—(a) Pruett tuff and (b) Crossen trachyte

FIGURE 3.—Looking westward from near the north side of Mt. Ord. Talus deposit on Mt. Ord in left foreground. From south to north in distance are: Cathedral Mountain, Haley Mountain, and the southern part of McIntyre Peak intrusive mass

Creek fault. Maravillas Creek heads on the southern slopes of the Mt. Ord dome and flows southeasterly across the Del Norte Mountains in Monument Spring quadrangle through Doubtful Canyon cut in folded and faulted Cretaceous and Paleozoic strata. Longer canyons in the northern Davis Mountains also oppose the dip of the volcanic layers.

Although several streams appear to be antecedent, they probably originated as consequents on now removed volcanic surfaces and were later superimposed on the buried structure. Great thicknesses of volcanic rock have been stripped from areas where stream courses show least adjustment to structure near the margins of the existing volcanic field. Erosional escarpments on the south and east, 300–1000 feet high, suggest that the volcanic series once extended far to the south and east of the present abrupt terminations. Possibly several hundred feet of lava and tuff covered the Del Norte Mountains and much of the Marathon dome. It does not seem likely, therefore, that Doubtful Canyon, now occupied by eastward-flowing Maravillas Creek, and Del Norte Gap, a wind gap east of Elephant Mountain, were initiated by southwest-flowing consequent streams, as suggested by King (1937, p. 18–19).

Upstream from the escarpments bounding Crossen and North Crossen mesas, only a few narrow, discontinuous, alluviated flats occur along the master stream valleys, but south of the escarpments these streams flow through wide flat alluviated valleys—largest is the Sheep-Calamity Creek valley, between Elephant Mountain and Crossen Mesa. A cutting cycle is now in progress, and the valley fill is trenched by nearly vertical-walled channels 5–20 feet deep.

Summary of Geologic History

Within the limits of the Cathedral Mountain quadrangle, the geologic record begins with deposition of the Word formation during Guadalupe time (Permian). The siltstone, sandstone, and dolomitic limestone of the Word and Capitan formations in the vicinity of Mt. Ord are forereef deposits laid down on the northwest side of the Hovey channel; both formations grade into massive reef deposits northeastward in the Glass Mountains.

The angular unconformity between marine Permian strata and the overlying Bissett conglomerate (Triassic; Dockum) on the northwest slope of the Glass Mountains is evidence of post-Permian, pre-Triassic uplift and erosion. No Jurassic deposits are known in this part of Trans-Pecos Texas, and, presumably, from late Permian to early Cretaceous time this area stood above the sea and from late Triassic on was subjected to erosion. Middle Mesozoic tilting and warping are demonstrated in the Glass Mountains by angular unconformity with overlying Cretaceous and folding of the Bissett conglomerate. If this conglomerate and Permian rocks younger than the Capitan limestone ever were deposited in the area of the Mt. Ord dome, they were removed by post-Permian, pre-Cretaceous erosion. The structurally and topographically high position of the Mt. Ord area in early Cretaceous time probably resulted from the post-Bissett, pre-Cretaceous deformation.

Overlapping of Comanche marine strata shows that the area occupied by Mt. Ord and the northern Del Norte Mountains and most of the Glass Mountains was high in early Cretaceous time; a low ridge probably connected the northern Del Norte and Glass mountains.

There is some evidence that a basin existed in the central part of the Cathedral Mountain quadrangle when the early Cretaceous sea came in. In the Argo Oil Corporation's Mitchell Bros.-State No. 1 well, located on Whirlwind Mesa about 4 miles west of the southwest corner of the Cathedral Mountain quadrangle, only 600 feet of Cretaceous rocks was encountered (DeFord, *in* Goldich and Seward, 1948, p. 37), approximately the same thickness as the Cretaceous section exposed at Mt. Ord. But at Cienega Mountain, about midway between these two points, nearly 1000 feet of Cretaceous sediments is exposed. The Cretaceous in the Argo well was not subdivided, so the formations cannot be compared. The observable Cretaceous record ranges from a conglomeratic sandstone probably equivalent to the Maxon sandstone of the Marathon region (late Trinity or early Fredericksburg) to the Boquillas limestone (middle or upper Eagle Ford). Yet

Comanche Peak limestone and Walnut clay of early Fredericksburg age and Glen Rose limestone of Trinity age outcrop in the Del Norte Mountains in Monument Spring quadrangle along the east side from the southern boundary to within 3 miles of Mt. Ord, and these beds dip west and southwest off the Del Norte Mountains; therefore they probably occur in the subsurface in the southeastern part of the Cathedral Mountain quadrangle.

The Cretaceous period closed with the Laramide uplift and orogeny which produced the ancestral Del Norte-Santiago-Carmen mountains and initiated a broad structural depression to the west of this range; also, the Marathon dome was probably initiated at this time. As the late Eocene age of the basal Tertiary volcanic unit, the Pruett tuff, is now established, the initial Laramide orogeny can be dated as late Cretaceous, pre-upper Eocene; widespread erosion of the Cretaceous beds prior to deposition of the Pruett tuff indicates a late Cretaceous and/or Paleocene or early Eocene age for the deformation.

The long period of post-Cretaceous erosion ended with the explosive volcanic activity which blanketed the surface with volcanic ash. The first showers of ash may have drifted in from sources outside the immediate area, but coarse igneous gravel in conglomerate beds in the upper part of the Pruett formation were probably from near-by sources. Explosive eruption was intermittent, and streams were active on the surface of the ash beds, as shown by the poorly sorted, lenticular stream deposits of tuffaceous sandstone and conglomerate interbedded with the tuff layers. Lenticular beds of fresh-water limestone, largely of organic origin, at different horizons in the Pruett tuff indicate the existence of shallow lakes. Judging from the types of fossil vertebrates and plants found in the basal tuff in the Tierra Vieja and Davis mountains, a warm temperate climate with abundant rainfall prevailed during upper Eocene time in Trans-Pecos Texas.

The intermittent explosive volcanism which supplied the fine pyroclastic material in the Pruett tuff was followed by quieter eruption of acidic lava, the Crossen trachyte. The great lateral extent suggests outpouring from a number of fissures. The Crossen trachyte was then subjected to erosion which produced a hill-and-valley topography; some valleys were cut completely through it and into the underlying Pruett tuff.

Spreading of lower flows of the Sheep Canyon basalt over the deeply incised surface of the Crossen trachyte initiated a new cycle of volcanic activity which produced basaltic, trachybasaltic, andesitic, and trachyandesitic flows which make up the Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt units of the Buck Hill volcanic succession. Beds of limestone and tuffaceous materials between flows in the lower unit, and deeply weathered and eroded surfaces within and at the tops of the units, are evidence that effusive activity was recurrent over a long period of time.

The Duff formation records the beginning of another long cycle of intermittent explosive volcanism, ending with deposition of the Tascotal formation. Flood-plain and channel deposits of tuffaceous sandstone and conglomerate at several horizons in the Duff and Tascotal formations testify to many quiescent intervals. A thick succession of rhyolitic, trachytic, trachyandesitic, and basaltic flows in the Duff formation (Decie member) in the Alpine (15-min.) quadrangle, tongues of which extend southward into northern Cathedral Mountain quadrangle as thin intercalations in the tuff beds, shows that effusive activity followed periods of explosive eruption and indicates that important sources of the volcanic material in the Duff formation were located near by. That slow downwarping was initiated in late Duff time and continued through Tascotal time in an area embracing Goat and Cathedral mountains is suggested by the apparent thickening of the Tascotal formation and the Rawls basalt and abundant conglomerate in the Tascotal and Duff formations. The Duff formation, Mitchell Mesa welded tuff, and Tascotal formation, a group of dominantly rhyolitic tuffaceous formations in the Cathedral Mountain quadrangle and southward, are possibly Miocene.

After a period of quiescence, during which the Tascotal formation was eroded, extrusive activity was renewed, and basic lavas of the Rawls basalt spread over a large area. The

source of the Rawls flows is unknown. The unit is thickest in the southwestern part of Tascotal Mesa quadrangle, and sources which supplied that region may have been in the Bofecillos Mountains. The Cathedral Mountain quadrangle contains only a few erosional remnants. No extrusive igneous rocks younger than the Rawls flows occur, but late Tertiary and Quaternary erosion probably stripped off much of the younger volcanic material and Rawls basalt. Definite dating of the Rawls basalt unit is not now possible but it may be lower Pliocene.

Probably when northwest structural trends (Cordilleran) were developed in this part of Trans-Pecos Texas, after extrusion of the Rawls lava flows and before a late period of syenitic intrusive activity, folding of the volcanic layers resulted in a regional dip of 2°–4° N. and NW. in the southern Davis Mountains. Following or perhaps in part contemporaneous with this regional crustal movement, syenitic magmas intruded the Buck Hill volcanic succession, producing local doming and faulting. It was probably mostly during this period that the Marathon dome was uplifted. Sometime after intrusion of the syenitic magmas, and prior to alluviation of present valleys, large-scale normal faulting developed along lines generally parallel with axes of the earlier folding.

Extrusive vulcanism may easily have been contemporaneous with emplacement of the syenitic intrusive bodies. Several slender conical peaks of intrusive syenite, exposed by deep erosion, may be volcanic necks. Eagle Peak vent, younger than the major normal faulting, is positive evidence of later extrusion. After igneous activity ceased, possibly in late Pliocene, consequent streams developed on a broad volcanic field which extended far to the east and southeast of the present limits of the Buck Hill volcanic series; the Davis Mountains are a relatively small erosional remnant. Since then erosion has been differential.

Economic Geology

No ore deposits are known in the Cathedral Mountain quadrangle. Cretaceous limestones in contact with intrusive igneous rocks can be seen only around Cienega Mountain, and little or no contact metamorphism occurs along the volcanic-intrusive contacts. Marmatization of Georgetown and Edwards limestones brought up with the Cienega Mountain syenitic intrusion produced sizable patches of marble and loose granulated limestone relatively free of contact metamorphic silicate minerals.

Agate is plentiful in amygdaloidal zones in all lava units. Highly prized plume and moss varieties are found in the Sheep Canyon and Cottonwood Spring basalts; banded pastel shades occur in the Crossen trachyte, and bloodstone is common in the Potato Hill andesite. Small stringers of milky-blue semi-precious opal occur locally in the Cottonwood Spring and Rawls basalts. Amethyst in small geodes is rare in the basaltic flows. Small euhedral crystals of analcime are abundant in the lowest basalt flow in the Duff formation on the southeast slope of Goat Mountain; clusters of stilbite, showing excellent cruciform twin development, and other zeolites occur at the head of the north branch of Walnut Draw in the Cottonwood Spring basalt.

The large dome beneath Mt. Ord is a possible oil trap, but the igneous cores exposed in many similar structural features in the vicinity suggest the possibility that the dome is underlain at shallow depths by an intrusive igneous body.

The supply of ground water is limited but adequate for ranching requirements. Water is obtained from wells ranging in depth from 25 to 75 feet in alluvium in the valley flats, to 100 to 400 feet in the volcanic rocks. Because of varying permeability of the rocks, a simple and uniform water table does not exist in the volcanic terrane. The water is pumped from wells by windmills into steel or concrete tanks located on high ground and then distributed by pipelines to watering places. Part of the supply is obtained by diverting surface run-off into large earthen tanks; some is furnished by small springs. Spring-fed flow from Calamity Creek is used for small-scale irrigation projects on the Bird and Nevill ranches.

Description of Selected Measured Sections

Location of the following sections, measured in connection with the detailed geologic mapping of

the Cathedral Mountain quadrangle, is shown by appropriate symbol on Plate 1.

Section 1—Maxon sandstone up through lower part of Duff formation, northwest side of Cienega Mountain

	Thickness (Feet)
Duff formation:	
41. Sandstone, conglomerate, and breccia, reddish brown, very hard, cemented with silica; grade sizes range from medium-grained sand to boulders more than 2 feet in diameter; aggregate in conglomerate composed of trachyte and felsitic igneous rocks and large blocks of red baked tuff; lenticular and cross-bedded	38
40. Tuff, red and gray, friable, medium-grained, conglomeratic in places; not well exposed	110
Total:	148
Cottonwood Spring basalt:	
39. Basalt, pinkish gray, weathers dark reddish brown, medium-grained, white speckled owing to abundant small micalike flecks of feldspar; vesicular zones contain much chalcedony; not well exposed; may be tuff layers concealed by debris	286
38. Tuff, gray, medium gray, friable (poorly exposed)	11
Total:	297
Sheep Canyon basalt:	
36. Basalt porphyry, dark brown, medium-grained, abundant large glassy pinkish and yellowish phenocrysts of labradorite	50
35. Basalt, grayish black, fine-grained, nonporphyritic	55
34. Tuff, pink and gray, baked, medium-grained	3
33. Basalt, grayish black, fine-grained, several vesicular zones, calcite abundant in vesicles	116
32. Basalt (?) covered	137
Total:	361
Crossen trachyte:	
31. Trachyte porphyry, dark reddish brown, fine-grained groundmass, abundant stubby phenocrysts of glassy feldspar; well-developed columnar jointing	228
Pruett tuff:	
30. Nearly pure volcanic tuff, gray, fine-grained, massive, contains greenish-gray shaly zones and some calcareous tuff	159
29. Not well exposed in line of section, tuff, gray, friable, lavender shaly zones toward top	85
28. Conglomerate, pink and gray; pebble-size gravel composed of gray, coarse-grained, calcareous tuff; matrix is pink, fine-grained tuff	22
27. Nearly pure volcanic tuff, gray, fine-grained, compact, thin- to thick-bedded, weathers into subrounded to angular fragments	20
26. Tuff, pink and gray, medium-grained, massive, highly calcareous, weathering produces pitted surfaces	5
25. Shale, dark red, fissile	11
24. Volcanic ash, pink to gray, fine-grained, dense to porous, massive, contains flecks of gray tuff; surface pitted by differential erosion; mostly covered	53
23. Conglomerate, mixture of gray, brown, and pink, poorly sorted; gravels range from granule to pebble size and are composed of well-rounded to fine-grained igneous rock and hard silicified tuff. Matrix composed of coarse-grained tuffaceous material; lenticular	12
22. Tuff, light gray, very fine-grained, thin to thick bedded, calcareous, slightly silicified; dense zones grade into porous, medium-grained material, has subconchoidal fracture, grades upward into pink, noncalcareous tuff	64
21. Nearly pure volcanic tuff, pale pink to gray, fine-grained, compact, massive, noncalcareous	32
20. Conglomerate, pinkish gray, weathers brown, poorly sorted, gravel well rounded, granule to cobble size (mostly pebble size), composed of indurated tuff, limestone, and fine-grained igneous rock. Matrix is fine-grained, calcareous tuff; contains lenses of medium- to coarse-grained tuffaceous sandstone; thick bedded	48
19. Tuff, gray, dense, calcareous, compact, alternates with pink, slightly calcareous, less compact tuff, thick bedded	11
18. Volcanic ash, pink, fine-grained, compact, massive, contains small flecks of gray tuff	20

17. Tuff, gray with pink zones, highly calcareous, medium- to coarse-grained, indurated, thick bedded.... 35
16. Tuff, light gray to white, noncalcareous, very fine-grained, compact, massive, contains small flecks of mica and tiny particles of a black mineral; forms gentle slope; poorly exposed..... 85
15. Tuff, light gray, calcareous, fine-grained, dense, subconchoidal fracture, thick bedded, contains flakes of mica..... 26
14. Tuff, reddish pink, fine- to medium-grained, hard, subconchoidal fracture, thick-bedded, poorly exposed..... 42
13. Fresh-water limestone and interbedded calcareous tuff, light gray to greenish gray, medium-grained, crystalline; tuff is fine-grained, very hard, conchoidal fracture, weathers brownish gray with rough pitted surface, thick bedded..... 26
12. Volcanic ash, greenish gray, fine-grained, massive, loose to compact, weathers dirty gray..... 4.2
11. Tuffaceous limestone, gray, finely crystalline, slightly silicified, thick-bedded..... 3.3
10. Tuff, greenish gray to pink, medium-grained, loose to compact, arenaceous, thick-bedded; weathers into nodular gravel..... 13
9. Tuff, light gray to white, very hard, siliceous, slightly calcareous, massive..... 9.5
8. Shale, black, fissile..... 10

Total:..... 798

Georgetown and Edwards limestone (undifferentiated):

7. Limestone, light gray, metamorphosed, friable, sugary zone alternating with harder recrystallized areas.. 125
6. Limestone, dark gray, marmatized; coarse-grained; fossiliferous, large gastropods and rudistids; (location of marble quarry)..... 100
5. Limestone, dirty gray, thick-bedded, medium-grained..... 50
4. Limestone, light gray, dark gray, and mottled, thin to thick bedded; contains thin beds of light yellowish-gray marl; fossiliferous, chert abundant in thin layers along bedding planes, irregular-shaped nodules, and narrow stringers; calcite veins in joints and fractures..... 150

Total:..... 425

Maxon (?) sandstone:

3. Conglomerate, granule to cobble; matrix fine- to coarse-grained quartz sandstone, cemented with silica; gravel composed of well-rounded and polished white vein quartz, black quartzite, and black and varicolored chert; thick-bedded, lenticular..... 66
2. Sandstone, light greenish gray, siliceous, well cemented, fine- to medium-grained, thick-bedded; interbeds of light greenish gray; arenaceous shale containing abundant pea-size rounded quartz and chert gravels..... 284
1. Sandstone and conglomerate; sandstone is light greenish to dark gray; fine- to coarse-grained quartz sand, coherent, thin to thick bedded, lenticular; conglomerate layers are lenticular, grains rounded, granule to pebble size, composed of quartz and chert, matrix is fine- to coarse-grained sandstone..... 16

Total:..... 366

Intrusive alkalic syenite (core of Cienega Mountain).

Total thickness measured:..... 2697

Section 2—Upper Crossen trachyte, Sheep Canyon basalt, Potato Hill andesite, and lower Cottonwood Spring basalt in east slope along Walnut Draw

Thickness (Feet)

Cottonwood Spring basalt:

6. Basalt, grayish brown, weathers to reddish brown, fine- to medium-grained, nonporphyritic, massive; white flaky grains of feldspar give the rock a speckled appearance; contains flow-breccia and ropy lava, numerous vesicular and amygdaloidal zones..... 189

Potato Hill andesite:

5. Decomposed andesite, highly weathered, tuffaceous appearance..... 5
4. Andesite, bluish gray, weathers dark reddish brown, fine-grained, porphyritic, massive; greenish in vesicular areas; abundant amygdules of chalcedony; weathers into thin sheets and slabs; weathered surface grades down into flow-breccia zone..... 57

Total:..... 62

Sheep Canyon basalt:
3. Highly weathered, tufflike basalt..... 3
2. Basalt porphyry, coal-black, weathers dark reddish brown, fine- to medium-grained; esicular and amygdaloidal with amygdules of chalcedony and calcite; abundant large, glassy, greenish and yellowish phenocrysts of labradorite; spheroidal weathering well developed in gullies..... 127
Total:..... 130

Crossen trachyte:
1. Porphyritic trachyte, vesicular, fine-grained, reddish brown and yellow; abundant stubby phenocrysts of anorthoclase (base not exposed)..... 26
Total thickness measured:..... 307

Section 3—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt on west side of Crossen Mesa, north of Torvea Canyon fault

	Thickness (Feet)
Cottonwood Spring basalt:	
13. Basalt flow, grayish black, fine-grained, nonporphyritic.....	66
12. Tuff, pinkish gray, hard, baked.....	11
11. Basalt flow, reddish brown, fine- to medium-grained, nonporphyritic, amygdaloidal at top, fillings of chalcedony and calcite.....	46
10. Basalt flow, reddish brown, fine-grained, nonporphyritic; vesicular zone 15 feet thick at top contains fillings of chalcedony and calcite; flow-breccia 10 feet thick at base.....	52
Total:.....	175
Potato Hill andesite:	
9. "Tuff," dirty gray, medium-grained, grades downward into weathered andesite.....	31
8. Porphyritic andesite, reddish brown, weathers greenish locally, fine-grained; contains abundant phenocrysts of yellowish plagioclase phenocrysts, some up to 1 inch long and half an inch wide; vesicular and amygdaloidal zone at top grades downward into massive lava; abundant chalcedony and calcite fillings.....	82
Total:.....	113
Sheep Canyon basalt:	
7. Tuff, dirty gray; contains fragments of basalt; grades downward into weathered basalt.....	23
6. Porphyritic basalt, dark greenish black, fine- to medium-grained; glassy plagioclase phenocrysts abundant locally.....	31
5. Porphyritic basalt, coal-black, weathers reddish brown, medium-grained, large glassy phenocrysts of plagioclase feldspar abundant; amygdaloidal top with chalcedony and calcite fillings.....	62
4. Tuff, light gray, medium-grained, compact.....	5
3. Tuff, light gray, medium-grained, compact.....	5
2. Porphyritic basalt, coal-black, weathers reddish brown, fine- to medium-grained; abundant glassy plagioclase phenocrysts; vesicular and amygdaloidal zones contain much chalcedony and calcite.....	39
1. Tuff, yellowish gray, medium-grained (poorly exposed).....	18
Total:.....	183
Crossen trachyte.	
Total thickness measured:.....	440

Section 4—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt, on spur between Calamity Creek and Sheep Creek

	Thickness (Feet)
Cottonwood Spring basalt:	
12. Basalt, dark grayish brown, fine-grained, nonporphyritic, white speckled owing to abundant mica-like flakes of feldspar, vesicular at top.....	38
Potato Hill andesite:	
11. Tuff, gray and pinkish gray, fine- to medium-grained, hard, baked, breaks with conchoidal fracture.....	14
10. Porphyritic andesite, bluish gray, weathers reddish brown; fine-grained groundmass, many stubby, glassy, plagioclase phenocrysts; vesicular top contains much chalcedony, some opal, a few quartz geodes; weathers into thin sheet and slabs; coarse flow-breccia zone at base.....	79
Total:.....	93
Sheep Canyon basalt:	
9. Basalt, fine- to medium-grained, with abundant large glassy, greenish, yellowish, and clear phenocrysts of labradorite (up to 2 inches long), coal-black on fresh break, weathers dull reddish brown.....	16
8. Tuff breccia, bluish gray, silicified, has conchoidal fracture, contains angular fragments of feldspar and quartz in fine-grained groundmass.....	9

7. Basalt, fine- to medium-grained, porphyritic, contains vesicular zones with much agate and jasper fillings, coal-black; weathers dull reddish brown and greenish gray 25
6. Limestone, gray, cherty, fossiliferous 3
5. Basalt, fine-grained, coal-black, weathers dull reddish brown and greenish gray; contains "stalactitic" or tubular rods 3/16 to 3/4 inch in diameter with cores composed of yellowish and reddish moss agate and an outside coating of dull chalcedony 26
4. Tuff, bluish gray, friable, with baked zones 5
3. Basalt, fine-grained, porphyritic with large glassy phenocrysts of labradorite; vesicular zone in upper 15 feet contains flow-breccia made up of large angular blocks of cindery and dense basalt; vesicular zone weathers a distinctive greenish color, small vesicules are filled with chalcedony and calcite (are also large geodal masses of calcite up to 6 inches in diameter), abundant banded and moss agate and jasper, veins of calcite and jasper cut the vesiculated zone; dense material is coal-black on fresh break, weathers reddish brown 70
2. Tuff breccia, reddish brown, hard, baked, has conchoidal fracture 1–2
1. Basalt, fine- to medium-grained, porphyritic with large glassy phenocrysts of labradorite, coal-black, weathers dull reddish brown; cores from spheroidal weathered masses abundant over the surface 97

Total: 250

Pruett tuff.

Total thickness measured: 381

Section 5—Pruett tuff and Sheep Canyon basalt, westward from large earthen tank in Chalk Valley up east-facing escarpment at north end of North Crossen Mesa

	Thickness (Feet)
Sheep Canyon basalt:	
12. Flow-breccia	20
11. Porphyritic basalt, black, weathers reddish brown, fine- to medium-grained, contains scattered glassy plagioclase phenocrysts	37
10. Tuff, gray, hard, fine-grained	20
9. Basalt porphyry, black, weathers reddish brown, large glassy plagioclase phenocrysts abundant; vesicular zone 15 feet thick near top	65
8. Flow-breccia	62
7. Basalt porphyry, black, weathers reddish brown, medium-grained, plagioclase phenocrysts abundant; upper 10 feet is vesicular with fillings of chalcedony and calcite	77
Total:	281
Pruett tuff:	
6. Limestone, gray, siliceous	10
5. Tuff, light greenish gray, medium-grained, thick-bedded	103
4. Tuff, yellowish gray, sandy, medium-grained, friable	5
3. Tuff, light greenish gray, fine- to medium-grained, thick- to massive-bedded, compact	36
2. Tuff, yellowish gray, fine-grained, alternating hard and soft layers	21
1. Tuff, pink and gray (not well exposed) ...	165
Total:	340
Alluvium.	
Total thickness measured:	621

Section 6—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt, southeast of Anderson ranch house, northward in slope at north edge of North Crossen Mesa

	Thickness (Feet)
Cottonwood Spring basalt:	
12. Basalt, grayish black, fine-grained, nonporphyritic; prominent flow-breccia about 10 feet thick in lower part	25
11. Basalt, grayish black, fine-grained, nonporphyritic, 15-foot vesicular zone at top, contains fillings of chalcedony and calcite	35
10. Basalt, grayish black, fine-grained, nonporphyritic, 5-foot vesicular zone at top	58
9. Tuff, gray, lenticular; poorly exposed ...	5
8. Basalt, grayish black, fine-grained, nonporphyritic; contains amygdaloidal and vesicular zones with chalcedony and calcite fillings	61
Total:	184
Potato Hill andesite:	
7. Weathered andesite	2
6. Porphyritic andesite, greenish gray, weathers dull brown, fine-grained, contains scattered glassy plagioclase phenocrysts	51
Total:	53
Sheep Canyon basalt:	
5. Basalt porphyry, black, weathers reddish	

brown, medium-grained, large glassy plagioclase phenocrysts are abundant... 26
4. Tuff, gray; poorly exposed..... 5
3. Basalt porphyry, black, weathers reddish brown, fine- to medium-grained; upper 15 feet is composed of coarse flow-breccia..... 82
2. Tuff, gray..... 5
1. Porphyritic basalt, coal-black, weathers reddish brown, some large plagioclase phenocrysts..... 41
Total:..... 159

Crossen trachyte.
Total thickness measured..... 396

Section 7—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt, near intersection of Calamity Creek fault and State highway No. 118, east of highway—up slope to northeast

Thickness (Feet)

Cottonwood Spring basalt:
6. Basalt, grayish black, fine-grained, nonporphyritic; vesicular and amygdaloidal zones contain appreciable fillings of chalcedony and calcite; probably 2 or 3 flows..... 102

Potato Hill andesite:
5. Tuff or highly decomposed andesite, gray, contains small fragments of lava.. 10
4. Andesite, grayish brown, fine-grained; contains scattered small pink plagioclase phenocrysts..... 72
Total:..... 82

Sheep Canyon basalt:
3. Highly weathered and decomposed basalt, gray, contains small weathered fragments of basalt, tuffaceous in appearance..... 8
2. Basalt porphyry, black, weathers reddish brown, medium-grained, large glassy plagioclase phenocrysts are abundant... 57
1. Tuff, gray, medium-grained (not well exposed)..... 25
Total:..... 90

Crossen trachyte.
Total thickness measured:..... 274

Section 8—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt, in slope east of Ash Creek, about 1 mile northeast of Anderson ranch house

Thickness (Feet)

Cottonwood Spring basalt:
5. Basalt, grayish black, fine-grained, nonporphyritic; 2 vesicular zones; probably 3 flows..... 101

Potato Hill andesite:
4. Andesite, greenish gray, weathers dull brown; contains a few small glassy plagioclase phenocrysts..... 41

Sheep Canyon basalt:
3. Tuff or highly decomposed basalt, gray. 5
2. Basalt porphyry, black, weathers reddish brown, fine- to medium-grained, abundant plagioclase phenocrysts..... 87
1. Tuff, gray (poorly exposed)..... 40
Total:..... 132

Crossen trachyte.
Total thickness measured:..... 274

Section 9—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt, in slope eastward from Calamity Creek, east of Bird ranch house

Thickness (Feet)

Cottonwood Spring basalt:
6. Basalt, grayish black, weathers grayish brown, fine-grained, nonporphyritic; vesicular zones contain fillings of chalcedony and calcite..... 103

Potato Hill andesite:
5. Andesite, greenish gray, weathers dull brown; slightly plagioclase phenocrysts..... 41

Sheep Canyon basalt:
4. Tuff or highly decomposed basalt, gray. 7
3. Basalt porphyry, greenish black, weathers reddish brown; abundant plagioclase phenocrysts; vesicular and amygdaloidal zones contain chalcedony and calcite..... 36
2. Tuff, gray (poorly exposed)..... 62
1. Porphyritic basalt, black, weathers reddish brown, medium-grained, contains scattered plagioclase phenocrysts..... 42
Total:..... 147

Crossen trachyte.
Total thickness measured:..... 291

Section 10—Duff formation, Mitchell Mesa welded tuff, Tascotal formation, and Rawls basalt, in southeast slope and escarpment of Goat Mountain

Thickness (Feet)

Rawls basalt:
21. Basalt, dark brown, fine-grained, contains large areas of massive, coarse flow-breccia; black chalcedony is abundant as a botryoidal coating and cavity filling; numerous geodes lined with quartz crystals..... 210

Tascotal formation:
20. Tuff, gray and yellowish gray, medium-

to coarse-grained; contains sandstone and conglomerate lenses; poorly exposed 190

Mitchell Mesa welded tuff:

19. "Rhyolite" porphyry (welded tuff), gray to pink groundmass contains abundant phenocrysts of quartz and anorthoclase, dense to vesicular; well-developed vertical jointing; unconsolidated zone at base 90

Duff formation:

18. Tuff, light gray, ashy, massive 240
17. Sandstone and conglomerate, brown and reddish brown, poorly sorted, cross-bedded, lenticular, shows scour-and-fill relations; sandstone is tuffaceous, fine- to coarse-grained; conglomerate composed of well-rounded igneous rock gravels ranging from granule to cobble in size, cemented with tuffaceous sandstone; thin layers of tuff are interbedded 90
16. Tuff, light gray, fine- to medium-grained, compact, massive 260
15. Basalt, grayish brown, vesicular and cavernous; calcite and zeolites abundant 40
14. Tuff, light gray, ashy; contains thin arenaceous lenses 340
13. Tuff, light gray to white, nearly pure volcanic ash 1–8 inches wide—two sets trending at right angles to each other; contains several beds of "mud pellet" conglomerate 100
12. Basalt, dark brown, highly weathered; contains analcime, natrolite, and calcite 10
11. Tuff, gray; poorly exposed 90
10. Sandstone and conglomerate, brown, lenticular, cross-bedded 15
9. Tuff, gray 10
8. Sandstone and conglomerate, brown, lenticular, cross-bedded 5
7. Tuff, pinkish gray, friable 15
6. Conglomerate, dark red, hard; well cemented, poorly sorted, well-rounded grains of igneous rock ranging from granule to cobble in size 3
5. Tuff, gray, poorly exposed 20
4. Sandstone and fine-grained tuff, indurated 6
3. Tuff, gray, friable, massive 70
2. Sandstone and conglomerate, reddish brown, mostly conglomerate with matrix of coarse-grained sandstone, igneous rock pebbles and cobbles well rounded 25
1. Tuff, gray, medium-grained, friable, massive 60

Total: 1399

Cottonwood Spring basalt.

Total thickness measured: 1889

Section 11—Sheep Canyon basalt, Potato Hill andesite, and Cottonwood Spring basalt, from lower slope of Mt. Ord westward across Ash Creek and State highway No. 118

	Thickness (Feet)
Cottonwood Spring basalt:	
11. Basalt, dark gray, fine-grained, nonporphyritic	15
Potato Hill andesite:	
10. Tuff or highly decomposed lava, dull red, medium- to coarse-grained, hard, baked toward top	15
9. Andesite flow, very fine-grained, reddish gray, weathers dark brown, nonporphyritic; contains vesicular zones, thin flow-breccia at base	55
Total:	70
Sheep Canyon basalt:	
8. Contact between Sheep Canyon and Potato Hill covered; weathered basalt (?)	3
7. Basalt, fine-grained, phenocrysts scarce, coal-black, weathers dull reddish brown.	12
6. Tuff, pinkish gray; poorly exposed	20
5. Basalt, fine- to medium-grained, contains glassy yellow and greenish phenocrysts of labradorite up to 3 inches long (most larger than ½ inch and less than 1½ inches), and large glassy, jet black phenocrysts of hypersthene (1–2 inches long), coal-black, weathers dull reddish brown; about 25 feet above the base is a vesicular zone containing appreciable calcite filling	83
4. Tuff breccia, gray, silicified; a very distinctive bed in the Sheep Canyon, only 5–10 feet thick and caps less-indurated rhyolitic tuff in most places	28
3. Basalt, fine-grained, coal-black, weathers dull reddish brown (greenish gray in gullies), contains scattered phenocrysts of labradorite; cindery vesicular zones with abundant yellowish brown jasper	149
2. Covered by alluvium along Ash Creek	132
1. Basalt, fine-grained, nonporphyritic, coal-black on fresh break, weathers dull reddish brown, platy jointing	27
Total:	454
Crossen trachyte.	
Total thickness measured:	539

Section 12—Pruett tuff and Crossen trachyte, in east-facing escarpment of Mt. Ord

	Thickness (Feet)
Crossen trachyte:	
6. Porphyritic trachyte, reddish-brown groundmass, abundant stubby phenocrysts of anorthoclase; vesicular zone near top; well-developed columnar jointing	265
Pruett tuff:	
5. Tuff, gray; covered by talus from overlying trachyte	210
4. Limestone and calcareous tuff, gray, siliceous	6
3. Tuff, red and gray; contains thin freshwater limestone interbeds; poorly exposed	88
2. Tuff, gray, calcareous, sandy at base	6
1. Tuff, gray; poorly exposed	170
Total:	480
Buda limestone.	
Total thickness measured:	745

Section 13—Pruett tuff, at locality where fossil vertebrates occur on west side of Chalk Valley

	Thickness (Feet)
6. Sandstone and conglomerate, light-gray to greenish-gray and pink, fine- to medium-grained sandstone, thin- to thick-bedded, alternating with lenticular beds of breccia conglomerate; pebbles in conglomerate are indurated tuff and fine-grained igneous rock, in medium- to coarse-grained tuffaceous matrix; conglomerate contains fragments and complete mammal bones (titanothere) and numerous high-spire gastropods	50
5. Tuff, light gray, argillaceous, fine-grained, soft, thick-bedded	15
4. Tuff or volcanic ash, light gray, fine-grained, sandy, compact, massive	35
3. Tuff, gray, fine-grained, contains thin layers of loose shaly tuff	23
2. Tuff (volcanic ash), light gray, fine- to medium-grained, massive compact	10
1. Volcanic tuff, purplish gray, fine-grained, loose to compact, not well exposed	188
Total thickness measured:	331

Section 14—Pruett tuff, in Mt. Ord basin

	Thickness (Feet)
11. Covered in line of section, tuff, gray	252
10. Limestone, gray, granular, contains stringers of siliceous material	8
9. Tuff, yellowish gray, soft, marly, thick-bedded	30
8. Limestone, gray, granular, massive	4
7. Tuff, yellowish gray, calcareous, soft, marly in appearance, weathers into irregular-shaped nodules, massive	15
6. Tuff, yellowish gray (purplish in places), friable, medium-grained, thin- to thick-bedded, contains hard dense layers that stand up in ledges	15
5. Tuff, gray, medium-grained, friable, thick-bedded, grades upward into hard, reddish, fine-grained tuff at top	30
4. Limestone, gray, crystalline	3
3. Tuff, light gray, friable, thick-bedded	37
2. Limestone, gray, coarse-grained, with stringers and irregular areas of quartz and chalcedony	3
1. Tuff, gray, weathers yellow, brown, thick-bedded, arenaceous zones, cut by numerous narrow clastic dikes of fine-grained tuffaceous material	80
Total thickness measured:	477

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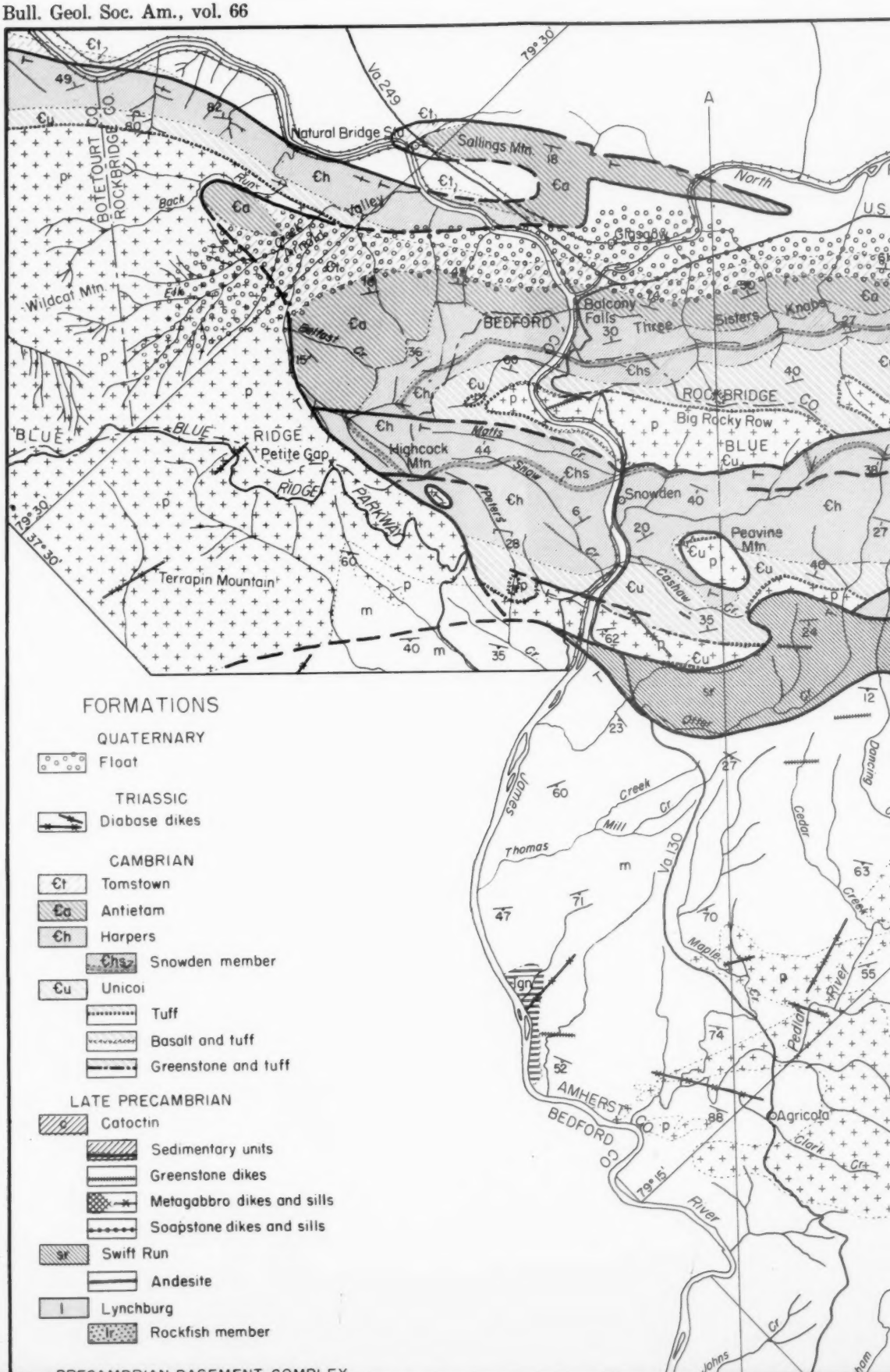
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Balcony Falls
Three Sisters
Knobs
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ROCKBRIDGE CO.
Big Rocky Row
BLUE RIDGE
Petite Gap
BLUE RIDGE PARKWAY
Highcock Mtn.
Snowden
Peavine Mtn.
Cashaw Cr.
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Maple
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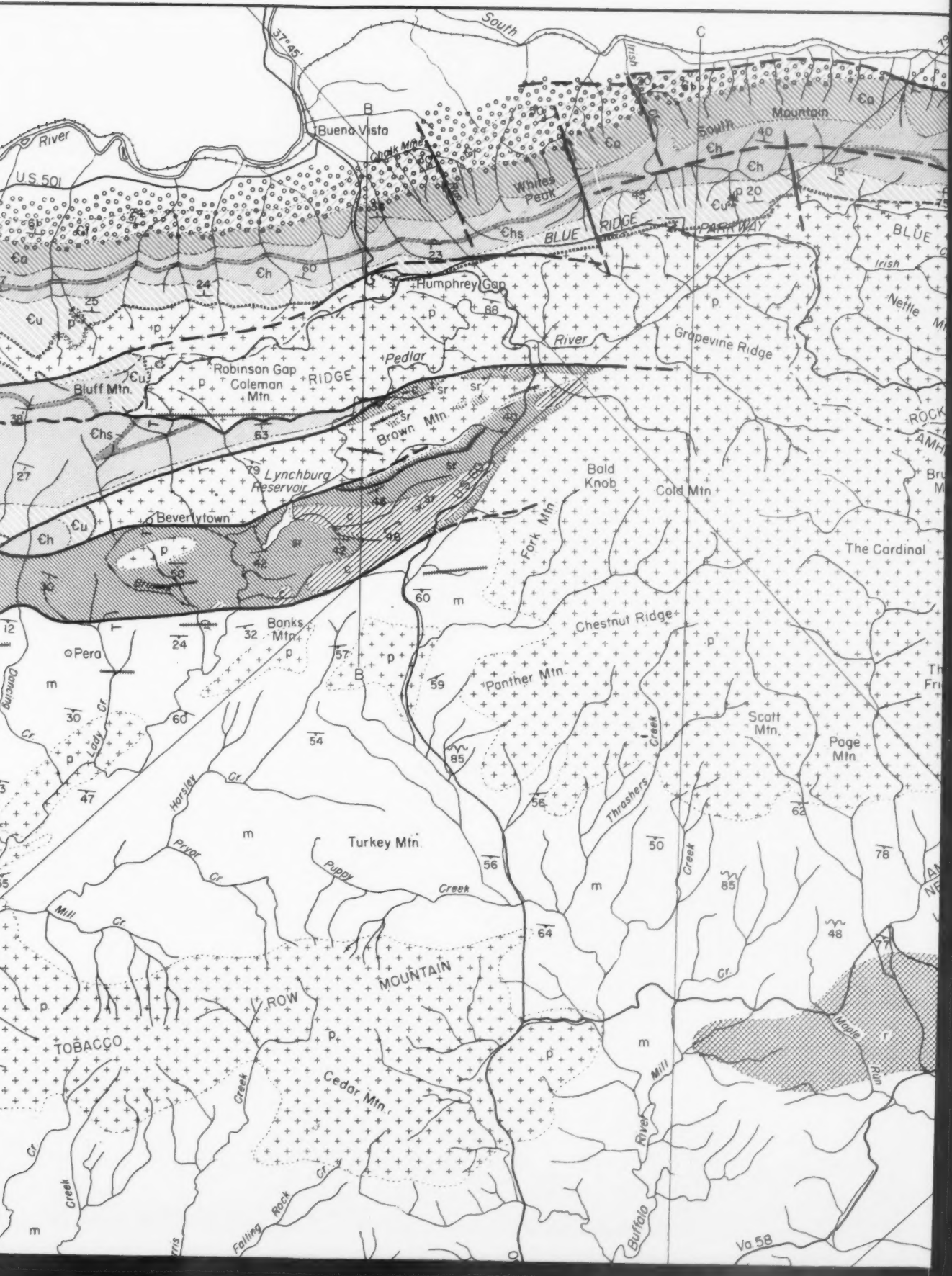
A
FORMATIONS
QUATERNARY
Float
TRIASSIC
Diabase dikes
CAMBRIAN
Ct Tomstown
Ca Antietam
Ch Harpers
Chs Snowden member
Cu Unicoi
Tuff
Basalt and tuff
Greenstone and tuff
LATE PRECAMBRIAN
C Catoctin
Sedimentary units
Greenstone dikes
Metagabbro dikes and sills
Soapstone dikes and sills
Sr Swift Run
Andesite
L Lynchburg
Rockfish member
PRECAMBRIAN BASEMENT COMPLEX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Buena Vista
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Robinson Gap
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Bluff Mtn.
RIDGE
Pedlar
River
Brown Mtn.
Lynchburg Reservoir
Beverlytown
Bald Knob
Cold Mtn
Fork Mtn
Grapevine Ridge
The Cardinal
Chestnut Ridge
Panther Mtn
Scott Mtn.
Page Mtn
Banks Mtn.
Pera
Turkey Mtn
Horsley Cr
Pryor Cr
Puppy Creek
Mill Cr
MOUNTAIN
TOBACCO
ROW
Cedar Mtn.
Falling Rock Cr
Buffalo River
Va. 58
Irish
Neffle
ROCK
Thrashers Creek
Maple Run
Mill River
C

South
River
79°15'
Irish
Creek
Mountain
Buena Vista
White's Peak
BLUE RIDGE PARKWAY
Whetstone Ridge
Tye River Gap
Cellar Mtn
St Marks R
Minebank Mtn
Humphrey Gap
Pedlar
River
Grapevine Ridge
Nettle Mtn
Panther Mtn
Montebello
ROCKBRIDGE CO
NELSON CO
AMHERST CO
Brown Mtn
Bald Knob
Cold Mtn
Fork Mtn
Brush Mtn
Wolf Ridge
Porters Ridge
Maintop Mtn
North Fork
White Rock Overlook
Va 56
South Fork
Crabtree Falls
The Cardinal
Chestnut Ridge
Panther Mtn
Scott Mtn
Page Mtn
The Friar
Shoe
The Priest
Three Ridges
Tyro
Piney
Rocky Run
Cub Creek
Turkey Mtn
Puppy Creek
Thrashers Creek
Little Mtn
Cat Rock Mtn
Massies Mill
Mars Knob
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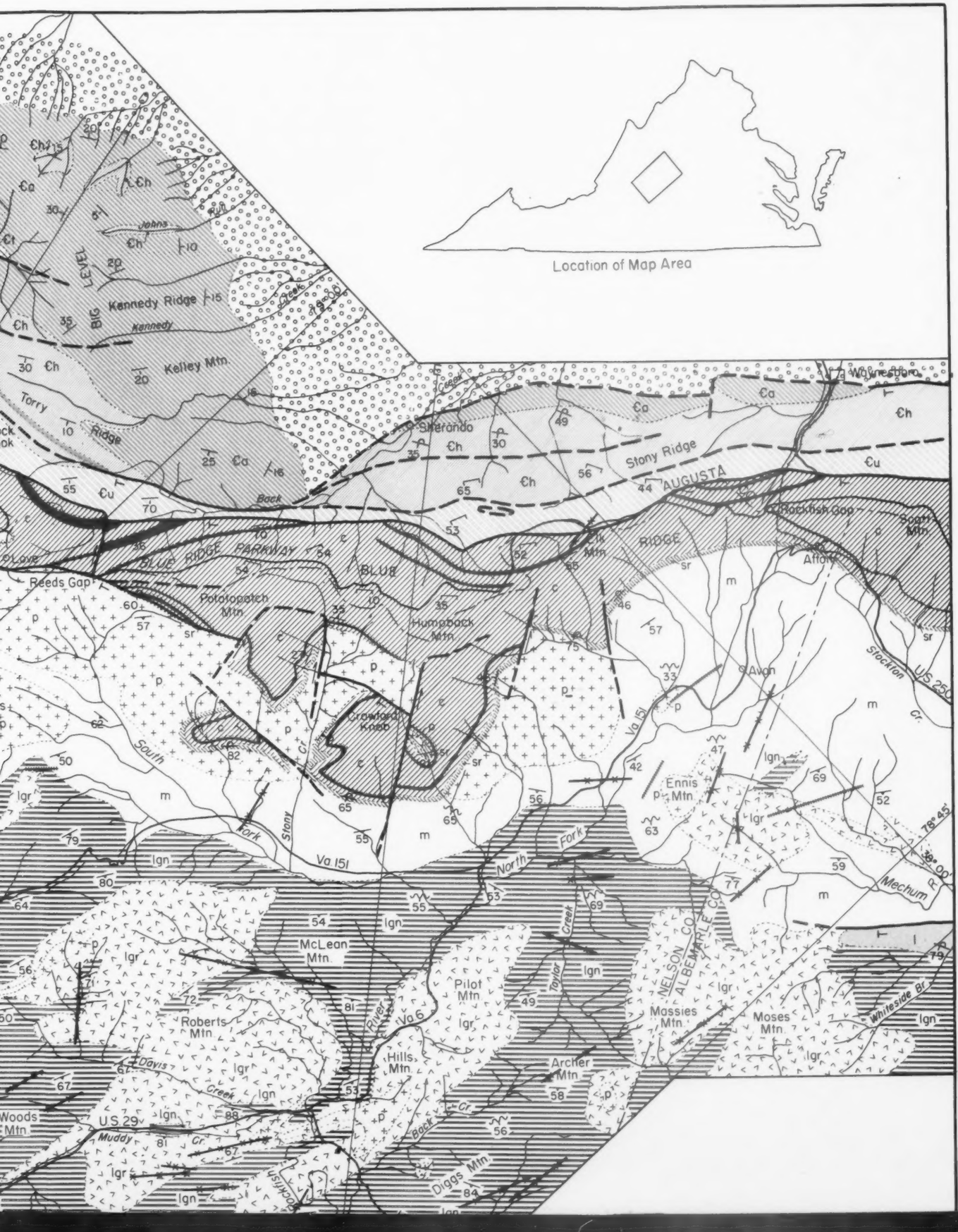
Location of Map Area
Kennedy Ridge
Kelley Mtn.
Torry Ridge
Stony Ridge
AUGUSTA
Waynesboro
Rockfish Gap
Scott Mtn
Afton
Avon
Reeds Gap
Potatopatch Mtn.
Humpback Mtn.
Crawford Knob
Ennis Mtn.
McLean Mtn.
Pilot Mtn.
Roberts Mtn.
Hills Mtn.
Archer Mtn.
Massies Mtn.
Moses Mtn.
Woods Mtn.
Diggs Mtn.
Mechum
Whiteside Br
Stockton
US 250
US 29
Va 151
Va 6
South Fork Stony
North Fork
Taylor Creek
Davis Creek
Muddy Cr.
Back Cr.
NELSON CO.
ALBEMARLE CO.
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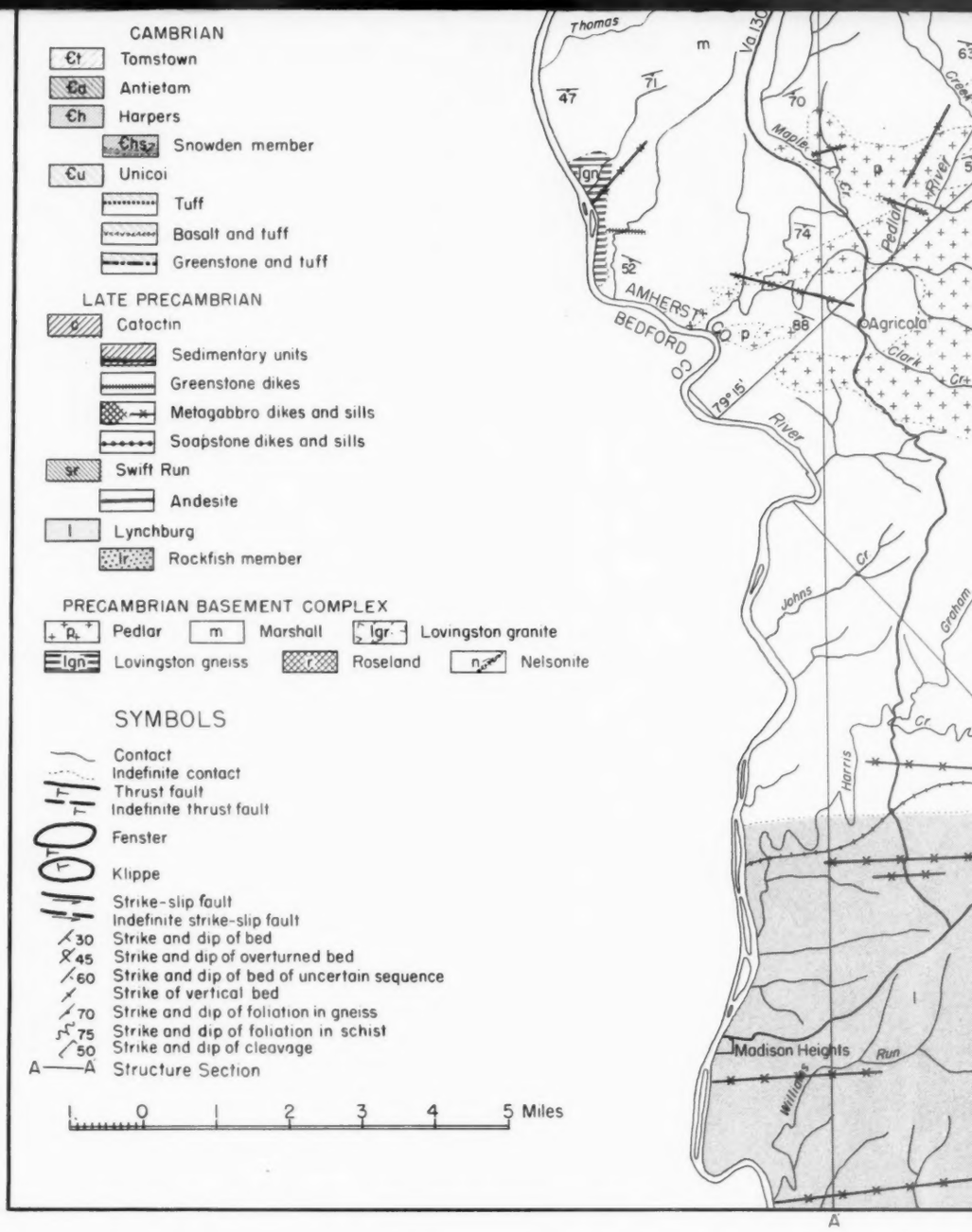
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Sedimentary units
Greenstone dikes
Metagabbro dikes and sills
Soapstone dikes and sills
sr Swift Run
Andesite
l Lynchburg
Rockfish member
PRECAMBRIAN BASEMENT COMPLEX
pz Pedlar
m Marshall
lgr Lovingston granite
lgn Lovingston gneiss
r Roseland
n Nelsonite
SYMBOLS
Contact
Indefinite contact
Thrust fault
Indefinite thrust fault
Fenster
Klippe
Strike-slip fault
Indefinite strike-slip fault
30 Strike and dip of bed
45 Strike and dip of overturned bed
60 Strike and dip of bed of uncertain sequence
Strike of vertical bed
70 Strike and dip of foliation in gneiss
75 Strike and dip of foliation in schist
50 Strike and dip of cleavage
A—A Structure Section
0 1 2 3 4 5 Miles
Thomas
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Maple
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Johns Cr
Graham
Harris Cr
Madison Heights
Williams Run
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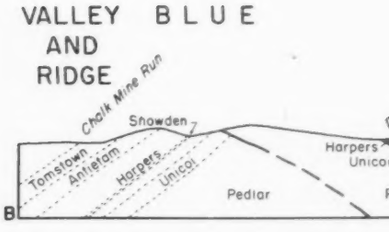
VALLEY AND RIDGE
BLUE
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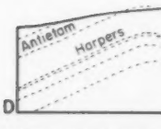
Antietam
Harpers
Unicoi
Pedlar
B

BLUE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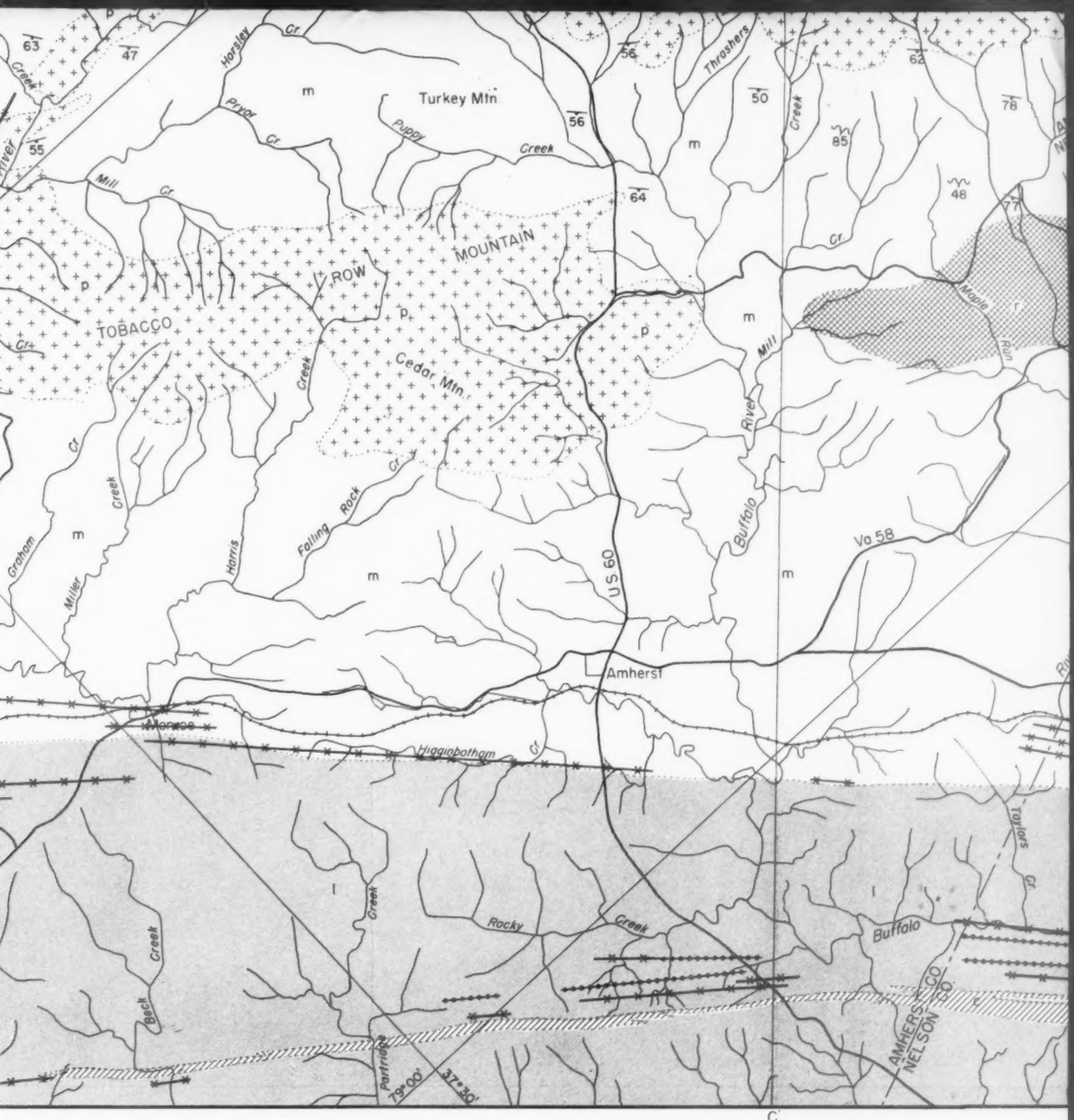

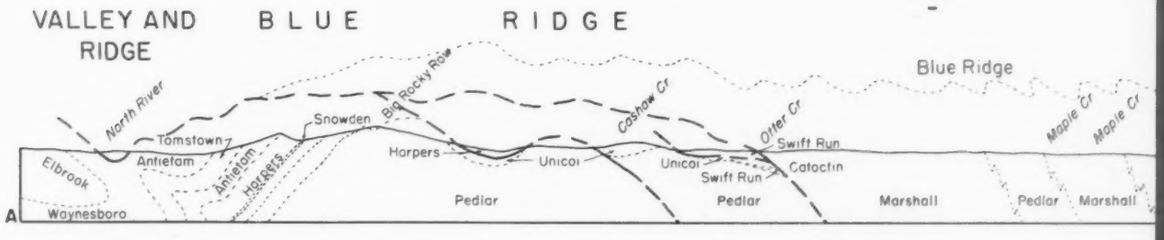

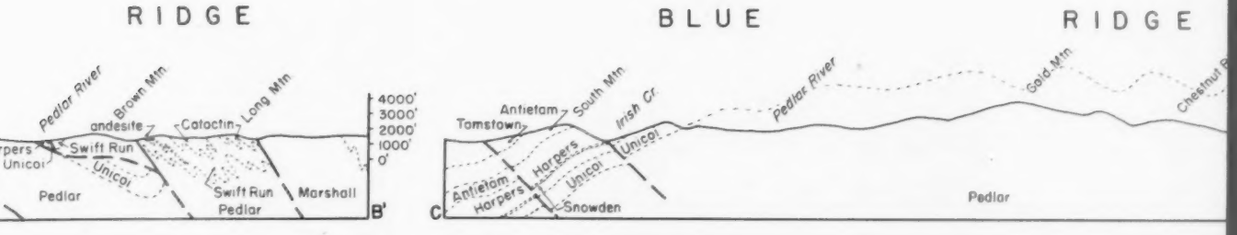

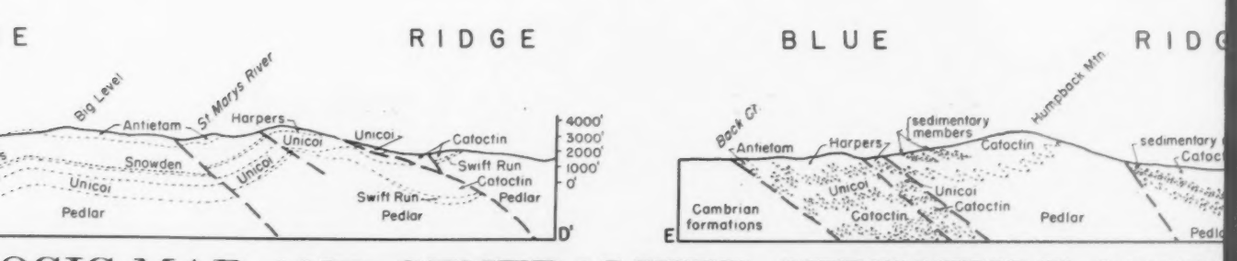

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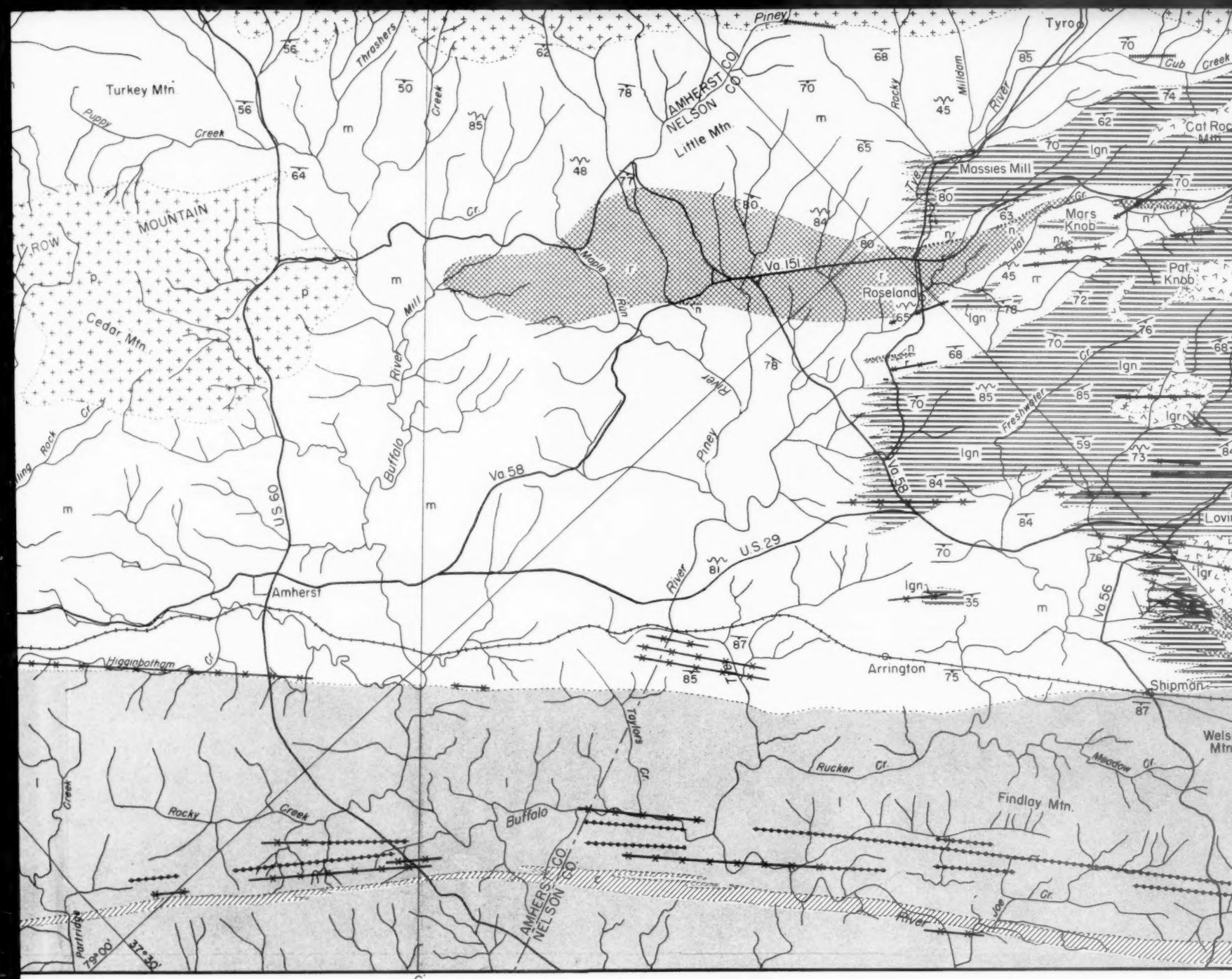

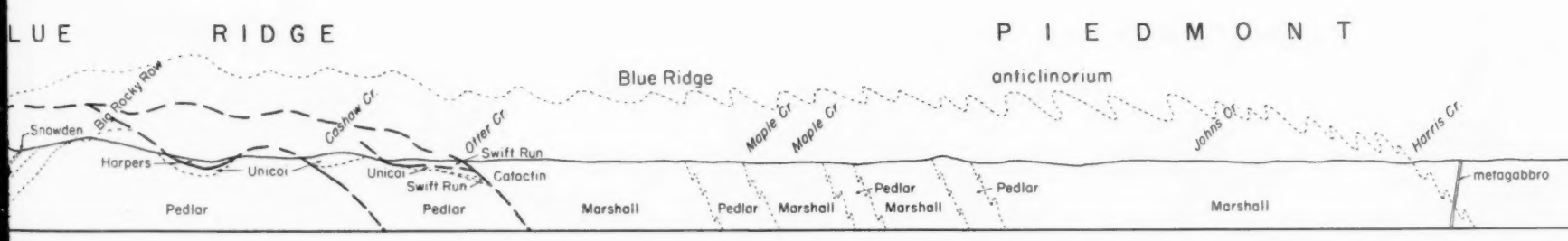

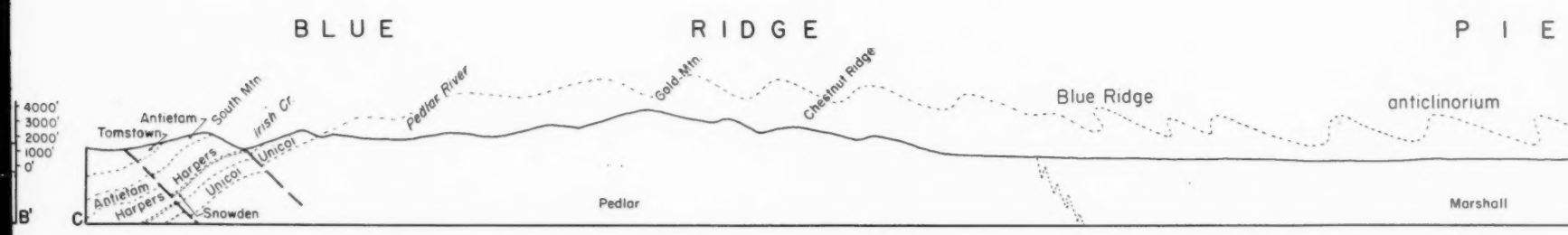

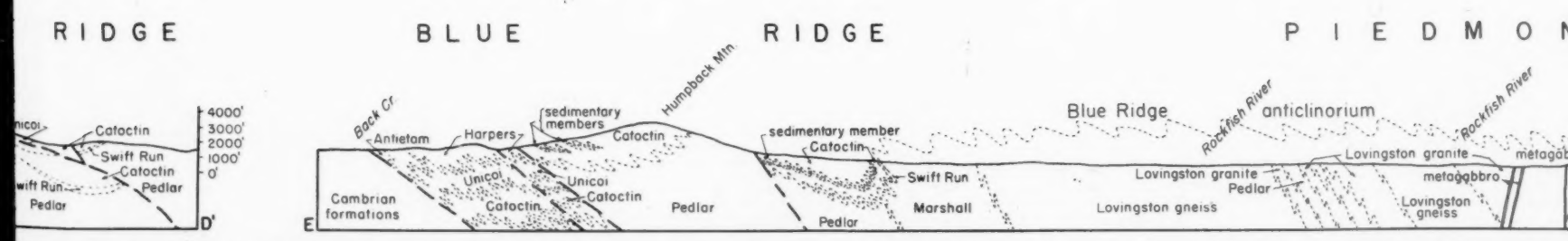

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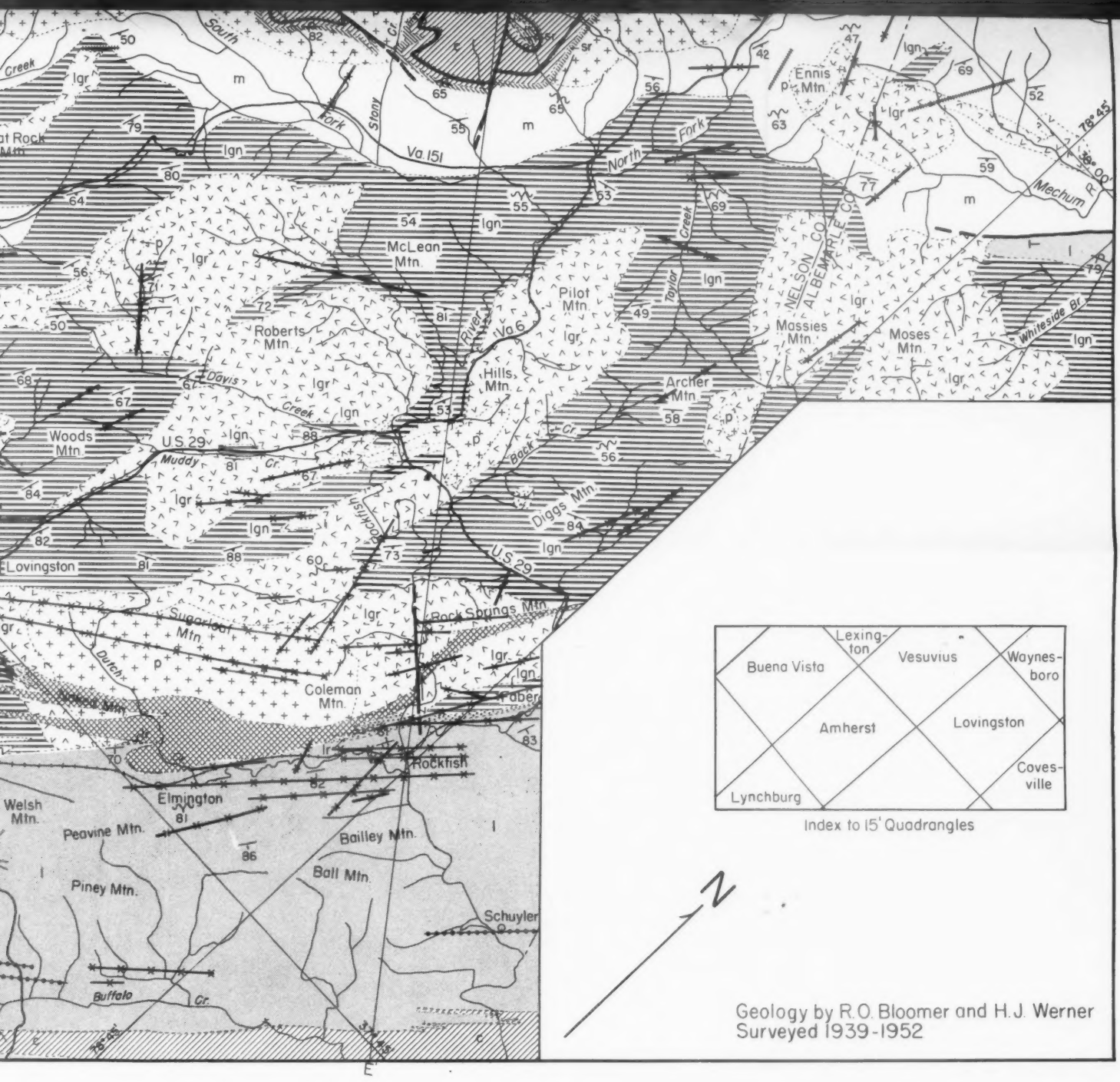

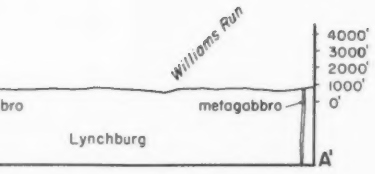

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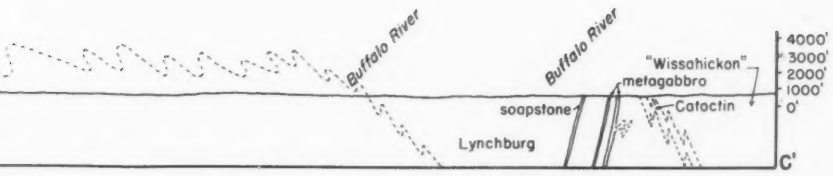

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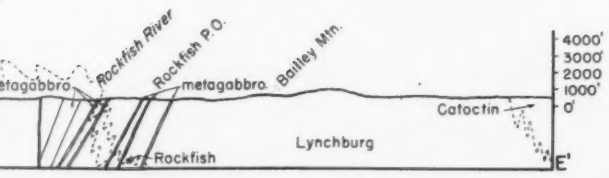

N CENTRAL VIRGINIA

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 66, PP. 579-606, 4 FIGS., 4 PLS. MAY 1955

GEOLOGY OF THE BLUE RIDGE REGION IN CENTRAL VIRGINIA

BY ROBERT O. BLOOMER AND HARRY J. WERNER

ABSTRACT

The Blue Ridge region in central Virginia extends from the southeastern margin of the Valley and Ridge province across the Blue Ridge into the Piedmont province. Across this span formations are sequentially continuous, so the Precambrian formations of the Piedmont are conformably related to the Cambrian formations of the Valley and Ridge. Extensive exposures of the Early Cambrian Chilhowee group reveal lithologic and facies variations that suggest certain geosynclinal relations and inconsistency in the use of several sets of formation names. The overlap of the Late Precambrian including the Catoctin greenstone, classified as spilite, and the relations of the Chilhowee group define a eugeosyncline to the east and a miogeosyncline to the west separated by an undation along which the Blue Ridge eventually formed.

The Catoctin Mountain-Blue Ridge anticlinorium is described as an epeirogenic uplift instead of a complex flexure fold. A dominant cleavage, independent of folding, is recognized as a thrust cleavage related to faulting.

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Introduction

The Blue Ridge region of central Virginia extends northeast about 46 miles from Arnold Valley in Rockbridge County south of James River to Rockfish Gap in Augusta County, and southeast about 25 miles from the Valley and Ridge province across the Blue Ridge into the Piedmont province (Fig. 1; Pl. 1). This region comprises an area of about 1000 square miles in the Buena Vista, Lexington, Vesuvius, Waynesboro, Covesville, Lovingston, Amherst, and Lynchburg 15 minute quadrangles.

Here the Blue Ridge region is particularly suited to detailed geological studies because:

(1) None of the formations in the Piedmont, Blue Ridge, and Valley and Ridge provinces of the area is structurally isolated, and interprovincial relations are fully revealed.

(2) Some of the rocks are similar to Blue Ridge formations in southwestern Virginia and Tennessee and some to Blue Ridge formations in northern Virginia, West Virginia, and Maryland (Table 1; Fig. 4).

(3) The Late Precambrian Catoctin and Swift Run formations (Stose and Stose, 1946, p. 18–22; King, 1950b, p. 9–14) locally disappear from beneath the conformably overlying Unicoi formation of Early Cambrian age (Butts, 1940, p. 36) because of overlap.

For many miles northeast and southwest of the region, thrust faults intervene between the Blue Ridge formations and the Valley and Ridge and Piedmont formations and interfere with inter-provincial correlations (Geologic Map of Virginia, 1928); within the Blue Ridge thrust faults interrupt the stratigraphic sections and mylonitize the formations, concealing full thicknesses and obscuring lithologic characteristics. The Elkton area in northern Virginia as does the central Virginia region, contains a section of formations stratigraphically continuous from well within the Blue Ridge into the Valley and Ridge province (King, 1950b).

Acknowledgments

The writers' work in central Virginia was done under the auspices of the Virginia Geological Survey with financial aid from the National Research Council, St. Lawrence University, and the Office of Naval Research (Contract No. N9 ONR-85501; Project No. NR 081-099).

Richard R. Bloomer, Richard Coogan, Wallace DeWitt, Warren Gilman, William Isachsen, and Robert Neuman were diligent assistants in the field. P. B. King, J. R. Hadley, John Rodgers, and E. Cloos conferred with the writers in the field, encouraged the preparation of this paper, and contributed much in the way of discussions.

Arthur Bevan, while State Geologist of Virginia, selected the area for detailed study and assigned the writers to the project. Dr. Bevan's interest and attention is largely responsible for the scope of the work included in this report. Marshall Kay and John Rodgers read the manuscript and offered many helpful suggestions.

To each of the organizations and individuals herein acknowledged, the writers extend their thanks.

Previous Work

The first geologic studies of the Blue Ridge were made by William Maclure (1809, p. 426) and W. B. Rogers (1884, p. 204–206, 461–462) during the first half of the nineteenth century. Rogers' work was not published until after his death.

Between about 1870 and 1885, W. M. Fontaine and H. D. Campbell made significant contributions. Fontaine (1875, p. 424), concluded that the formations in the Blue Ridge thicken southeastward and are represented among the rocks in the Piedmont. The geosyncline concept (Knopf, 1948, p. 649–670), in which "Appalachia" was recognized to the southeast, developed at the time of publication and, hence, Fontaine's concept was ignored until recently (Bloomer and Bloomer, 1947, p. 103; Bloomer, 1950, p. 781; Kay, 1951, p. 9; King, 1950a, p. 653; Brown, 1953, p. 89–94).

H. D. Campbell (1885, p. 472) studied the geology of James River gorge and published a cross section that recent studies show to be remarkably valid in stratigraphic details and structural interpretation.

During the present century other studies have been made, but these are limited and con-

cerned mainly with certain mineral deposits, the description of certain formations, or specific stratigraphic problems.

Marshall granite, hypersthene granodiorite, and Roseland anorthosite. With the exception of the anorthosite attributed by Watson and

TABLE 1.—FORMATIONS IN THE BLUE RIDGE REGION OF VIRGINIA

	Northern Virginia	Central Virginia	Approx. thickness (Feet)	Southwest Virginia	
Early Cambrian	Tomstown dolomite	Tomstown dolomite	1000–1500	Shady dolomite	
	Antietam quartzite	Antietam quartzite	700–900	Erwin quartzite	Chilhowee group
	Harpers formation	Harpers formation	800–1200	Hampton shale	
	Weverton quartzite				
		Unicoi formation	400–500	Unicoi formation	
	Loudoun formation				
Late Precambrian	Catoctin formation	Catoctin formation	0–2500		
	Swift Run formation	Swift Run formation	0–1000	Mount Rogers series	
	Lynchburg gneiss	Lynchburg gneiss	2000–5000		
	Basement complex	Basement complex		Basement complex	

STRATIGRAPHY

General Statement

Resting upon a basement complex of Precambrian gneisses and granitic rock, the stratigraphic succession in the Blue Ridge region of central Virginia includes seven formations (Table 1) which consist of metasedimentary quartz-oligoclase-biotite gneisses, metagraywackes, spilitic greenstones, metatuffs, conglomeratic graywackes, subgraywackes, arkoses, quartzites, and high-grade dolomites.

Minor folds, close-spaced thrust faults, cleavage, and rock flowage conceal the original thicknesses of the stratigraphic units so that only generalized estimates can be made (Table 1).

Basement Complex

General statement.—According to published reports (Watson and Taber, 1913; Watson and Cline, 1916, p. 193–234; Geologic Map of Virginia, 1928; Jonas, 1935, p. 47–60; Jonas and Stose, 1939, p. 575–593; Moore, 1940, p. 629–645; Ross, 1941), the basement complex consists of several large, subjacent bodies of orthomagmatic origin mapped as Lovingston granite gneiss (also quartz monzonite gneiss), Cline (1916, p. 210) and Moore (1940, p. 629–645) to the magmatic segration of the hypersthene granodiorite, each of the masses is believed to be a genetically separate body. Bloomer (work in progress), however, concludes that all the subjacent bodies in the basement complex were formed by the granitization of metasedimentary rocks.

Basement complex gneiss.—This uniformly medium-grained, quartz-oligoclase-biotite schist and gneiss with granoblastic bands and micaceous folia a fraction of an inch thick has long been identified as Lynchburg gneiss (Geologic Map of Virginia, 1928). Bloomer (1950, p. 760–768) has found, however, that the Lynchburg is a younger formation that rests unconformably upon the basement complex. Although the basement complex gneiss, erroneously identified as Lynchburg gneiss, comprises a large mappable mass to the southwest, in central Virginia it appears only in numerous elongate inclusions (skialiths) in the Lovingston, Marshall, and Roseland formations. These inclusions lie parallel to the regional foliation and range from a fraction of an inch to 10 feet thick and from a few inches to several hundred feet long. The contacts with the enclosing rocks are in some places sharply defined and in others they are replacement boundaries an inch or more wide;

the ends are gradually tapered, bifurcated, and delicately feathered. The writers believe them to be slightly granitized relics (skialiths) and not xenoliths, infolded younger rocks, or mylonite (Moore, 1940, p. 631).

Lovingston formation.—Jonas (Geologic Map of Virginia, 1928) defined this gneissic and granitoid formation from exposures near Lovingston, Nelson County, Virginia. It forms a mappable body about 25 miles long and 8 miles wide. Across a contact zone about 100 feet wide the rock grades into the Marshall formation with changes in composition, granularity, and structure. To the southeast it is unconformably overlain by the Late Precambrian Lynchburg gneiss. Other bodies as much as 3 miles long and 2 miles wide are elongated parallel to the regional foliation contained in the Marshall formation.

The gneiss and granite consist of quartz, potash feldspar, oligoclase-andesine (An30), and biotite. The gneiss is a dark-gray, medium-grained rock with prominent biotite folia and porphyroblasts of potash feldspar as much as 4 inches in diameter. It surrounds the granite which is a granulose rock containing biotite as irregular, equidimensional aggregates a fraction of an inch in diameter and as randomly oriented grains.

Marshall formation.—Comprising the major part of the basement complex, this formation was named on the Geologic Map of Virginia (1928) for exposures near Marshall, Fauquier County, Virginia. It is a gray or green, uniformly medium-grained gneiss consisting of quartz, potash feldspar, oligoclase-andesine (An30), and biotite. Quartzo-feldspathic bands that average about an eighth of an inch thick are separated by filmlike folia of bleached and chloritized biotite. This rock grades into the basement complex gneiss, Lovingston, and granodioritic formations.

Pedlar formation.—The formation heretofore defined and mapped as hypersthene granodiorite forms most of the basement complex of the Blue Ridge northeast of Roanoke, Virginia, and many masses surrounded by the Marshall and Lovingston formations in the Piedmont. Because it consists of an assemblage of granitic, granodioritic, syenitic, quartz dioritic, anorthositic, and unakitic rocks undifferentiable in the field as well as certain complex mineral and fabric relations, the writers conclude a formation name is required. They here propose the name Pedlar formation from exposures along the upper reaches of Pedlar River in the northwestern part of Amherst County in central Virginia.

In the Piedmont and along the southeastern foot of the Blue Ridge, this formation grades into the Marshall and Lovingston formations, but within the Blue Ridge it is unconformably overlapped by a sequence of Late Precambrian and Early Cambrian formations that extend into the Valley and Ridge province to the northwest. It is a green, white, or red, coarse-grained, granulose rock showing a palimpsest foliation in vague traces and porphyroblasts up to 4 inches in diameter. It consists of potash feldspar, oligoclase-andesine (An30), oligoclase (An20), and quartz in variable proportions with some hypersthene and diopside as accessories.

Roseland anorthosite.—This oval body about 13 miles long and 2.5 miles wide in the middle of the basement complex was named by Ross (1941, p. 2) from exposures near Roseland, Nelson County, Virginia, and first classified as anorthosite by Watson and Taber (1913, p. 68). In the Piedmont it is surrounded by the Marshall formation and in the Blue Ridge it is surrounded by the Pedlar formation.

It is a white or green, coarse-grained, locally granulated, granulose, monomineralic rock consisting of oligoclase-andesine (An30). Along the margins especially, there are large, tabular grains and veins of blue quartz and inclusions of basement complex gneiss oriented parallel to the regional foliation. Nelsonite consisting of medium- to coarse-grained ilmenite and apatite in roughly equal amounts forms dikelike bodies along the contact of the Roseland anorthosite with Marshall formation.

Late Precambrian

Lynchburg gneiss.—Named by Jonas (1927, p. 844–845) for exposures in Lynchburg, Virginia, across James River from Madison Heights, this metasedimentary formation unconformably overlies the basement complex and conformably underlies Catoctin greenstone. It overlaps the basement rocks from east to

west and has an outcrop width of 4.5 miles and an unknown thickness in the Piedmont; it is only partly represented by 0–400 feet of graywacke and tuff in the Swift Run formation in the Blue Ridge (Bloomer, 1950, p. 753–783). In the core of an anticlinorium, between the main mass of the Lynchburg in the Piedmont and the edge of the overlap in the Blue Ridge, in the medial portion of the intervening basement complex, there is a locally faulted isoclinal syncline of the Lynchburg about 1000 feet wide and 50 miles long, between Batesville in Albemarle County (Fig. 1) and Madison in Madison County, Virginia (Gooch, , Personal communication).

Bloomer (1950, p. 760–768) claims that a major part of the rock mapped as Lynchburg gneiss about 12 miles southwest of James River (Geologic Map of Virginia, 1928) is part of the basement complex, while the rock in the vicinity of Aldie, Loudoun County, in northern Virginia (Geologic Map of Virginia, 1928), which Keith (1894, p. 324) implies is typical Early Cambrian Loudoun, is Lynchburg gneiss. The name Lynchburg is recommended (Bloomer, 1950, p. 766) despite the priority of the name Loudoun because beginning with Keith the older name is firmly established for the formation at the base of the Paleozoic sequence in the northeastern part of the Blue Ridge (King, 1950b, p. 16). The Fauquier formation named by Furcron (1939, p. 37–41) is another duplication, probably equivalent to the Lynchburg.

The writers have traced the Lynchburg northeast and southwest from its type locality (Fig. 1); and find that in some places along and across the strike it is only slightly metamorphosed and in others it is in the middle grade of metamorphism. Some of the slightly metamorphosed rock resembles Early Cambrian rock in the Blue Ridge. The underlying unconformity is well defined by conglomerate, in some places but not in others, which might account for the duplication of names and erroneous mapping.

The writers recognize as Lynchburg all the metasedimentary rocks between the Catoctin greenstone and the basement complex in the southeastern limb of an anticlinorium, which extends from well within the Piedmont province into the main mass of the Blue Ridge (Pl. 1). Where the Catoctin in the Piedmont gradually thins and disappears near Lynchburg, Virginia, the Lynchburg formation is conformably overlain by the Evington group (Brown, 1953, p. 91–96) which replaces the Wissahickon formation (Geologic Map of Virginia, 1928). No indication of a "Martic fault" (Geologic Map of Virginia, 1928) or other faults of mappable significance was found between the Lynchburg or Catoctin and rocks to the southeast in the Piedmont province.

The Lynchburg consists of an undetermined thickness of conglomeratic gneiss, biotite gneiss, pebble quartzite, and phyllite. Except for open folds on James River at Madison Heights, bedding modified by boudinage is parallel to prominent foliation that strikes northeast and dips steeply southeast. On the cleavage planes (foliation), which seem to parallel the axial planes of folds, crinkle folds define a lineation in the phyllites. Approximately normal to the axes of these crinkle folds, elongated grains of biotite and sericite express lineation that lies in the cleavage plane. In pebble quartzites, some elongation of the quartz clasts is approximately parallel to the strike of the foliation. The cobbles and boulders in the conglomeratic gneiss are elongated partly owing to a shear system that strikes 30°–50° from the strike of the foliation. The echelon displacement along these shear planes across the cobbles and boulders has caused an elongation with an axis that lies between the *b* fabric axis defined by crinkle folds and the *a* fabric axis defined by the orientation of biotite and sericite.

The conglomeratic gneiss named Rockfish conglomerate by Nelson (1932, p. 456–457) from exposures near Rockfish, Nelson County, Virginia, occurs in the base of the Lynchburg in lenticular bodies as much as 2 miles long and 1000 feet across the outcrop. This rock grades downward 10–100 feet into the basement complex with a diminution in the number of clasts and the disappearance of bedding. This gradational contact and the similarity of composition and foliation indicate that the conglomerate was not deposited upon the unweathered, eroded surface of the basement complex, but rather upon a saprolite from which it was derived.

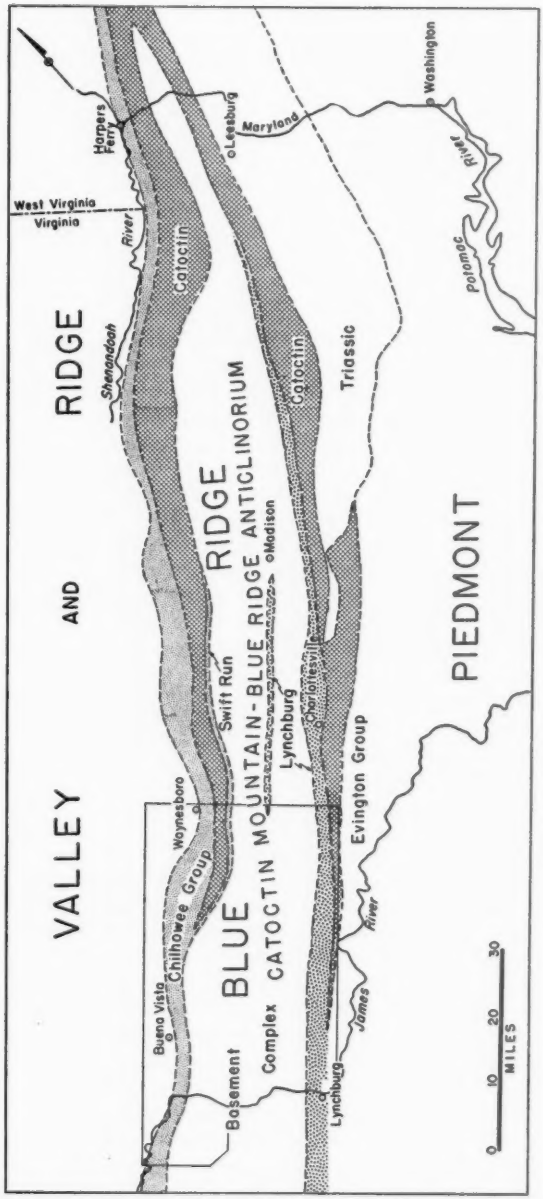

FIGURE 1.—INDEX MAP OF THE BLUE RIDGE REGION IN VIRGINIA

The Rockfish member of the Lynchburg has a coarse-grained matrix containing many well-rounded clasts of granite from a fraction of an inch to 24 inches in diameter and a few other feet thick is most abundant in the lower part of the formation. Where the Rockfish conglomerate is absent, this gneiss rests upon the basement complex and looks like the Marshall

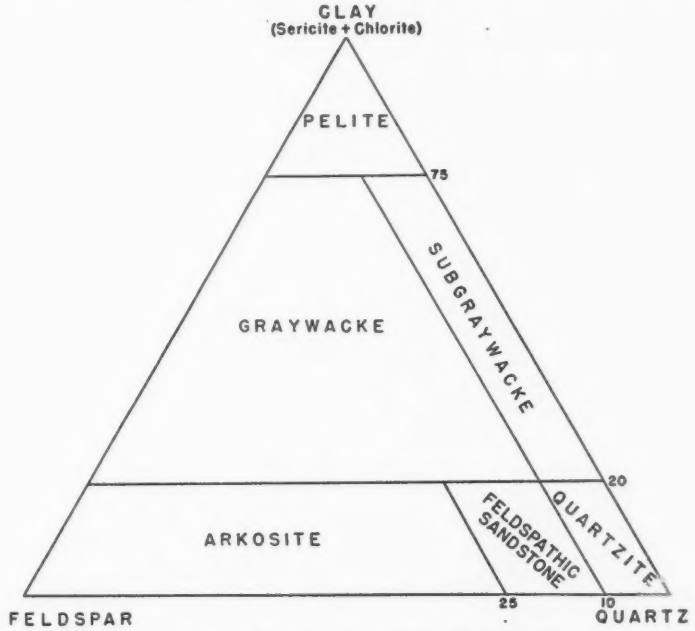

FIGURE 2.—CLASSIFICATION OF CLASTIC SEDIMENTS
According to Pettijohn (1949, p. 227)

clasts including quartz pebbles and discoid-shaped fragments of medium-grained biotite gneiss. The granite clasts doubtlessly were derived from the Lovingston and Pedlar formations, and the biotite gneiss clasts probably from skialiths of basement complex gneiss. The matrix is composed of lithic and mineral fragments and some indigenous crystalloblastic minerals. The clastic minerals are mainly quartz, potash feldspar, and oligoclase-andesine (An30); the crystalloblastic minerals are biotite, quartz, and oligoclase (An20). The biotite forms prominent folia that enwrap the clasts and also separate quartzo-feldspathic bands about half an inch thick.

Above the conglomeratic gneiss, the Lynchburg consists of irregularly interbedded biotite gneiss, pebbly quartzite, and phyllite. The biotite gneiss in beds from a few inches to many formation and basement complex gneiss. It is a uniformly medium-grained rock composed of biotite concentrated in thin schistose folia or disseminated in preferentially oriented grains in a granulose aggregate or quartz and feldspar. In both the gneissic and granulose rocks the most abundant minerals are quartz, oligoclase (An20), and biotite. The accessory minerals include epidote, ilmenite, apatite, pyrite, and rare grains of zircon. Biotite and quartz are in part neominerals and in part detrital grains and the oligoclase is a neomineral.

The pebbly quartzite forms thick beds separated by beds of phyllite and gneiss and is most abundant in the middle of the outcrop. It forms ridges and is a gray, massive rock composed of rounded, well-packed, blue and colorless quartz pebbles in a fine-grained matrix mainly composed of quartz, oligoclase (An20),

and sericite. The quartz clasts range from 0.10 to 0.50 inch in diameter. In individual beds the pebbles are notably equigranular.

blage of biotite, sericite, quartz, and oligoclase (An20) with sporadic metacrysts of almandine about 0.10 inch in diameter. Some of the phyl-

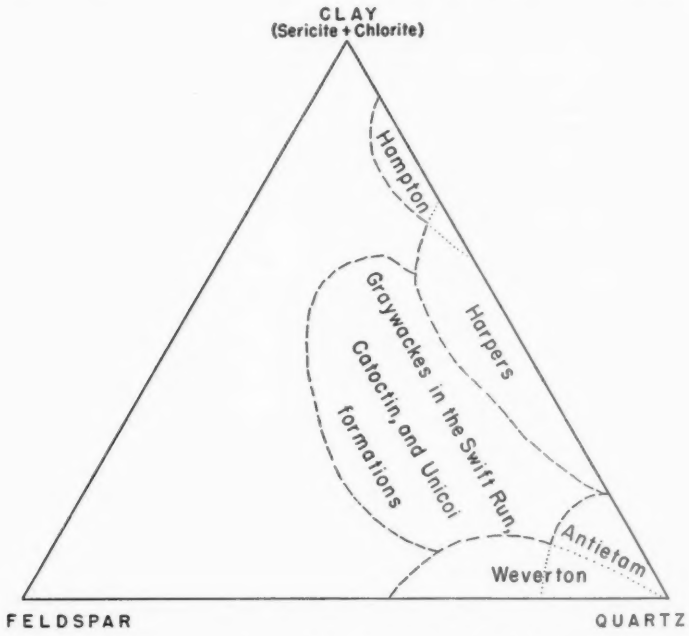

FIGURE 3.—COMPOSITION OF THE LATE PRECAMBRIAN AND LOWER CAMBRIAN FORMATIONS IN CENTRAL VIRGINIA

Based upon areal mapping and 52 modal analyses

The phyllite is interbedded with biotite gneiss and pebbly quartzite and is most abundant in the upper part of the formation. It is interbedded with greenstone in the lower part of the Catoctin formation southwest of Rockfish (Pl. 1). It is in part megascopically and microscopically similar to the Candler phyllite of the Evington group (Brown, 1953, p. 91–96). Jonas (1929, p. 507–509) believes the Candler is a diaphthorite (phyllonite) formed along the "Martic fault" from Wissahockon schist. The presence of delicate bedding, similar rock in the Lynchburg and in the Catoctin, and lack of petrographic evidence of retrogressive metamorphism invalidate Jonas' conclusion.

The Lynchburg phyllite with filmlike, finely arenaceous layers indicative of bedding is a gray to silvery schistose rock consisting of a uniformly fine-grained crystalloblastic assem-

lite contains not more than a few per cent graphite in submicroscopic particles in bands and blotches. Its origin has not been investigated.

Rocks of the Lynchburg formation are partly in the greenschist facies and partly in the albite-epidote-amphibolite facies of the metamorphic progression (Turner, 1948, p. 88, 93). The plagioclase (An20) is too calcic to be typical of the greenschist facies, and the almandine is symptomatic of the albite-epidote-amphibolite facies. Some of the phyllites and the pebbly quartzites contain an abundance of sericite and the plagioclase (An20) is transitional between facies.

The Lynchburg probably cannot be systematically mapped with respect to grade of metamorphism because it includes irregularly interbedded rocks of variable competence and

composition deposited as graywacke conglomerates (Rockfish), subgraywackes of siltstone to pebble-conglomerate grade, and shales (Figs. 2, 3). Some of the graywackes and subgraywackes were probably composed of only slightly altered crystalloblastic biotite, oligoclase-andesine (An30), and potash feldspar from the basement complex. These detrital minerals indicate a higher grade of metamorphism. Hence, near its northwestern contact with the basement complex the Lynchburg appears to be in a higher grade of metamorphism than farther southeast. Regionally, the grade is higher in the southeast.

Swift Run formation.—This formation was named by Stose and Stose (1946, p. 18–19) from exposures near Swift Run Gap in Rockingham County near Elkton in northern Virginia (King, 1950, p. 9–12) and consists mainly of 0–400 feet of graywackes, subgraywackes, and volcanics that unconformably overlie the basement complex and conformably underlie Catoctin greenstone in the Blue Ridge. In central Virginia it overlaps the basement complex from east to west. Hence, the Swift Run is the western margin of an overlapping mass of rocks (Pl. 1; Fig. 4), and is equivalent to the uppermost part of the Lynchburg (Bloomer, 1950, p. 760–775).

The Swift Run beds are from a fraction of an inch to about 20 feet thick and consist of graywackes, subgraywackes (Fig. 3, 4; Pl. 3), epidotized sandstone, andesite, tuffs, and greenstones. Where it overlies Pedlar migmatite, the lower part of the formation is a conglomeratic graywacke with clasts from about 0.50 inch to 5.0 feet in diameter composed of quartz, potash feldspar, and granite in an inequigranular matrix of quartz, feldspar, lithic fragments, and a pastelike aggregate of sericite and chlorite. Above the Marshall formation the graywacke is a medium-grained rock, without clasts, consisting of quartz, feldspars, and the pastelike aggregate of chlorite and sericite. Both the conglomeratic and nonconglomeratic graywackes grade into the underlying basement complex so the contact is not well defined. The Swift Run is separated from unaltered basement rocks as is the Lynchburg, by an ancient saprolite about 10–100 feet thick.

Where the Swift Run is 100 or more feet thick the graywacke grades upward into a uniformly fine-grained, thin-bedded subgraywacke composed of arenaceous grains of subrounded quartz in a matrix of sericite and chlorite.

In places near the overlap margin of the Swift Run, above the subgraywackes and below the overlying greenstone, there is an epidotized sandstone member up to 20 feet thick. It is cross-bedded, graded in beds several feet thick, and consists of equigranular, well-rounded, spherical quartz grains about 0.20 mm in diameter in a matrix of introduced epidote. Away from the greenstone contact the epidote content diminishes until the matrix is all silica (quartz). The greenstone or the lava from which it formed was extruded upon the packed but uncemented sand so that epidotizing solutions from the igneous rock permeated the pore spaces near the contact. Silica presumably from meteoric waters then permeated and cemented the unepidotized sand away from the contact.

Andesite forms a member about 85 feet thick in the medial part of the Swift Run between Lynchburg Reservoir and U. S. Highway 60 (Pl. 1). This rock is black, fine-grained, and coarsely cleaved with amygdules and rare lithophysae. It consists of laths of andesine (An40) that average 0.30 mm long in an ophitic fabric with the interstices filled with secondary minerals and remnants of biotite. Potash feldspar in granitoid grains 0.25 mm in diameter makes up less than 1 per cent. Secondary minerals that replace much of the feldspar and most of the biotite include, in order of abundance, chlorite, epidote, clinozoisite (?), sericite, magnetite, albite, and quartz.

Though considerably modified by secondary minerals, the andesite in the Swift Run contains readily determinable primary minerals, whereas the greenstone in the Swift Run and other formations is so modified by the secondary minerals that the primary minerals are masked or destroyed. These greenstones (Pl. 2) and the tuffs in the Swift Run are analytically indistinguishable from these rock types in the Catoctin and Unicoi formations, and are described in this paper only under the Catoctin formation.

Except along the steeply dipping, locally overturned contact with the basement complex and southwest of Lynchburg Reservoir between

FIGURE 4.—DIAGRAMMATIC INTERPRETATION OF DISTRIBUTION OF LITHOLOGIC UNITS IN LATE PRECAMBRIAN AND EARLY CAMBRIAN FORMATIONS IN BLUE RIDGE REGIONS OF VIRGINIA

two thrust faults the Swift Run rocks are only incipiently metamorphosed. Close to the steeply dipping contacts flattened, seemingly smeared clasts of quartz and feldspar are contained in a highly schistose aggregate of crystalloblastic sericite and chlorite. This rock, lacking crystalloblastic plagioclase or biotite, represents a low grade of greenschist facies (Turner, 1948, p. 93).

Southwest of Lynchburg Reservoir the Swift Run is represented by a phyllite formed from subgraywacke, containing much crystalloblastic sericite, chlorite, and quartz and meager amounts of crystalloblastic oligoclase (An20) and biotite. It represents the greenschist facies and is higher grade than the metagraywackes in contact with the basement complex.

The intimate association of the highly metamorphosed rocks with steeply dipping contacts and thrust faults, and the comparative lack of metamorphism away from these features, suggests that the rocks were metamorphosed by localized shear.

The greenstones in the Swift Run as well as in other formations (Pl. 2) contain minerals indicative of the greenschist facies, but these rocks were deuterically altered by hydrothermal solutions while in the inclosing rock the metamorphism was dynamothermal.

Catoctin greenstone.—Named "Catoctin Schist" by Keith (1894, p. 308–318) from exposures in Catoctin Mountain in northern Virginia, this formation in central Virginia spans an anticlinorium from within the Blue Ridge well into the Piedmont province (Fig. 4; Pl. 1). The associated formations differ in character across the region, and in the absence of the Catoctin their relationship would be much less certain.

In central Virginia the Catoctin consists of an undetermined thickness of greenstone with several mappable members composed of graywackes, arkoses, and tuffs. In Maryland (Jonas and Stose, 1938, Pl. 1), its outcrop splits on the nose of a fold forming two belts (Fig. 1) that extend far southwest. One of these belts extends along the crest of the Blue Ridge to a place near Tye River Gap where the greenstone is overlapped. The other belt is in the Piedmont separated from the Blue Ridge belt by about 20 miles. This belt disappears, presumably by overlap, near James River in the vicinity of Lynchburg, Virginia. The stratigraphic relations of the Catoctin vary; in the Piedmont it lies conformably above the Lynchburg gneiss and below the Candler phyllite (Brown, 1953, map) or "Wissahickon" schist (Geologic Map of Virginia, 1928; Fig. 4; Pl. 1); in the Blue Ridge in some places it conformably overlies the Swift Run and in others it unconformably overlies the basement complex. Despite disagreement (King, 1949a, p. 526–528; King, 1950b, p. 13–14; Stose and Stose, 1949, p. 311–315), the writers are certain the Catoctin is conformably overlain by the Lower Cambrian Unicoi or the partly equivalent Loudoun formation (Bloomer, 1950, p. 780–782). In both the Piedmont and Blue Ridge an alternating succession of greenstone and metasedimentary or sedimentary beds separate the Catoctin and the underlying Lynchburg and Swift Run formations. In the Blue Ridge in central Virginia a greenstone bed occurs extensively at the base of the Unicoi formation, and near White Rock Overlook on the Blue Ridge Parkway an alternating succession of greenstone and sedimentary beds separates the two formations (Fig. 4, Pl. 1).

The Catoctin consists of several members as much as 500 feet thick composed of coarsely clastic sedimentary rocks and tuffs contained within an undetermined thickness of greenstone. These members consist of thick beds of graywacke, arkose, and epidotized sandstone interbedded with a few inches to several feet of tuff. Some of the graywacke and arkose is conglomeratic with well-rounded pebbles of quartz and granite. The graywacke is a varicolored, coarse-grained rock composed of potash feldspar, plagioclase, and quartz in a matrix of sericite and chlorite. The arkose is a near-white, pink, or light-green, coarse- to medium-grained rock composed of potash feldspar, plagioclase, and quartz. Both the graywacke and arkose resemble granitic rocks where bedding and pebbles are indistinct. Locally the arkose in particular has the composition and megascopic texture of alaskite. These granite-like rocks are seen only from place to place and a search along the strike reveals gradational and lithologic stratification, cross-bedding, and pebbles.

The arkose in some members in the Catoctin grades upward into an epidotized sandstone like that in the Swift Run formation. Where no such

sandstone intervenes the arkose is epidotized beneath the overlying greenstone and consists of pink feldspar, white quartz, and green epidote, resembling a fine-grained unakite. The most accessible exposure of a section of one of these sedimentary members is on U. S. Highway 250 about 0.2 mile west of Rockfish Gap (Pl. 1).

The distribution of sedimentary members suggests that they are more numerous and thicker near the overlap margin of the Catoctin than farther east. They may represent fanlike sheets of sediment that spread from west to east upon flows of greenstone. If this is true the sedimentary members, significantly lacking any greenstone detritus, must converge with the Swift Run formation where they approach the basement complex (Fig. 4). However, all the coarsely clastic sedimentary rock in the Catoctin is not confined to the western margin. One well-defined member near the base of the formation is mapped in the main mass and in outliers of the Catoctin near the southeastern foot of the Blue Ridge several miles east of the overlap margin. At least one metasedimentary bed about 2 feet thick was recognized in the Catoctin section exposed on Rockfish River in the Piedmont belt near Schuyler, Virginia.

Tuffs in beds from a few inches to about 5 feet thick are interbedded with the coarsely clastic sedimentary rocks in the Swift Run, Catoctin, and Unicoi formations. These tuffs are reddish-brown, uniformly fine-grained, slaty rocks. They contain layers of graywacke and subgraywacke a fraction of an inch to a foot or more

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PLATE 2.—LATE PRECAMBRIAN AND LOWER CAMBRIAN GREENSTONES

FIGURE 1.—Catoctin greenstone about one mile northeast of Lynchburg Reservoir containing albitized andesine (A) and microcline (M) in a matrix of iron oxide minerals, chlorite, epidote, sericite, and other minerals; ×150, two nicols, oblique illumination

FIGURE 2.—Catoctin greenstone in Humpback Mountain containing albitized andesine (A) and microcline (M) in a matrix of iron oxide minerals, chlorite, epidote, sericite, and other minerals; ×170, one nicol, oblique illumination

FIGURE 3.—Greenstone in a dike in the basement complex on Cub Creek northeast of Tyro, Virginia; contains albitized andesine (A) in a matrix of iron oxide minerals, chlorite, epidote, sericite, remnants of augite (?), and other minerals; ×170, one nicol, oblique illumination

FIGURE 4.—Unicoi metavolcanics west of Bluff Mountain containing albitized andesine (A) in a matrix of iron oxide minerals, chlorite, epidote, sericite, remnants of augite (?) and glass, and other minerals; ×170, two nicols

PLATE 3.—LATE PRECAMBRIAN AND LOWER CAMBRIAN GRAYWACKES, SUBGRAYWACKES, AND QUARTZITES

FIGURE 1.—Graywacke in the Unicoi formation near Tye River Gap, like graywackes characteristic of parts of the Swift Run and Catoctin formations; contains quartz (Q) and perthitic microcline (M) in a partly authigenic matrix of sericite and chlorite; ×140, one nicol, oblique illumination

FIGURE 2.—Arenaceous graywacke in a sedimentary member in the Catoctin formation near Reeds Gap, like rocks of this type in the Unicoi formation; contains quartz (Q), andesine (A), and microcline (M) in a partly authigenic matrix of sericite and chlorite; ×70, two nicols

FIGURE 3.—Arenaceous subgraywacke in the Unicoi formation in James River gorge about one mile east of Snowden, Virginia; extensively represented in the Harpers formation and in some sections of the Swift Run formation; contains predominant quartz clasts (Q) in a matrix of sericite and chlorite in which ghosts of feldspar (F) are detected; ×35, two nicols

FIGURE 4.—Silty subgraywacke in the Harpers formation on Blue Ridge Parkway about 2 miles north of White Rock Overlook; extensively represented in the Unicoi formation; contains quartz clasts (Q) in a matrix of sericite and chlorite; ×170, one nicol, oblique illumination

FIGURE 5.—Quartzite in the Antietam formation in Big Level showing the recrystallization of the quartz clasts (arrow); such quartzites also in the Harpers formation; ×140, two nicols, oblique illumination

FIGURE 6.—Quartzite in the Harpers formation in James River gorge near Balcony Falls showing an iron oxide film on quartz clasts cemented by quartz; such quartzites also in the Antietam formation; ×140, one nicol, oblique illumination

FIGURE 1

FIGURE 2

FIGURE 3

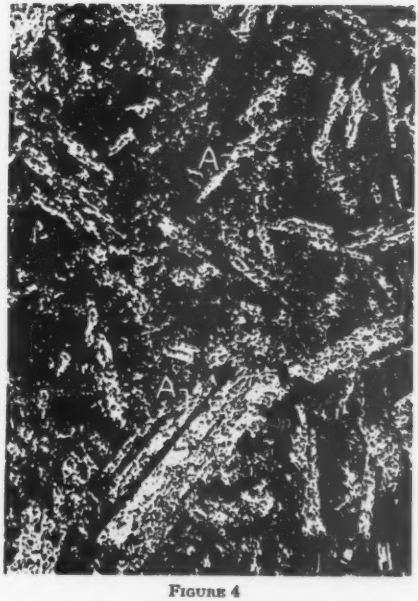

FIGURE 4

LATE PRECAMBRIAN AND EARLY CAMBRIAN GREENSTONES

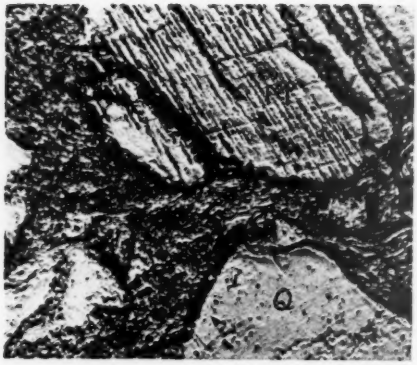

FIGURE 1

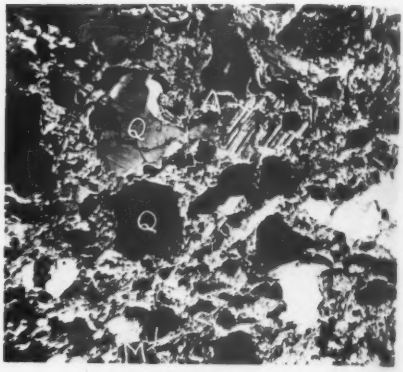

FIGURE 2

FIGURE 3

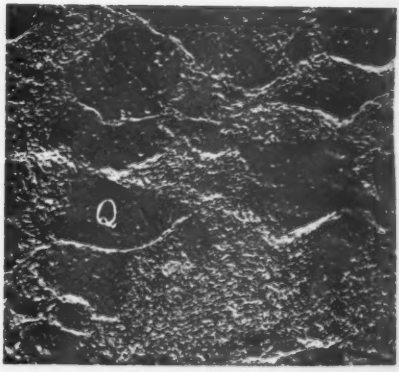

FIGURE 4

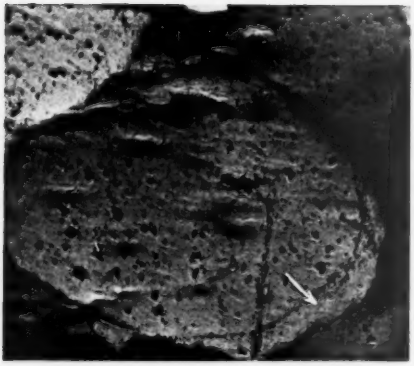

FIGURE 5

FIGURE 6

LATE PRECAMBRIAN AND EARLY CAMBRIAN GRAYWACKES, SUBGRAYWACKES, AND QUARTZITES

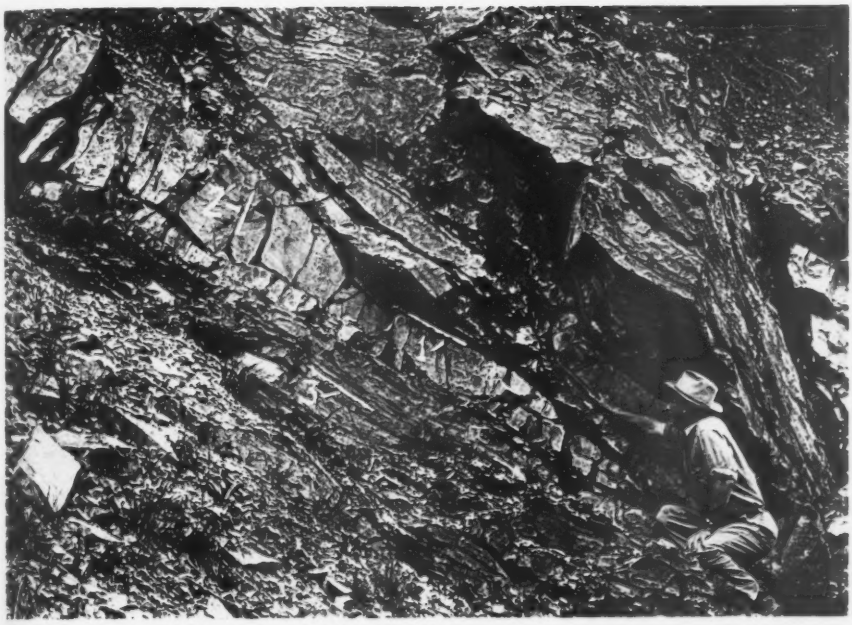

FIGURE 1

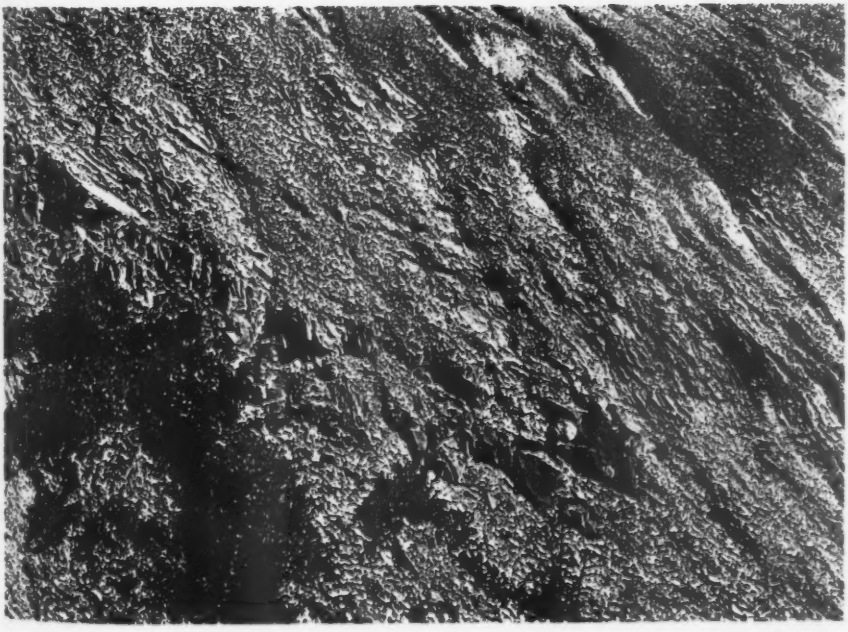

FIGURE 2

CLEAVAGE

thick that in places laminate the rock. This stratification includes some cross-bedding with an angularity of about 15°.

Microscopically these tuffs are characterized by an impalpable matrix and by 0–50 per cent of silt-grade, sub-rounded and angular grains of quartz, scant feldspar, and rare heavy minerals. Much of the tuffaceous matrix consists of optically anisotropic and opaque substances, but some may be isotropic. No glassy or devitrified shards have been positively identified, though some shapes suggest them. Some, if not most, of the anisotropic substances in the matrix are products of devitrification, and some of the isotropic matter may be glass. The opaque material is probably iron oxide.

In the absence of positively identified glass particles and definite shards, the classification of tuffaceous rocks in the Late Precambrian and Early Cambrian formations in central Virginia may be questioned. However, the abrupt transition within conglomeratic graywacke to thin tuffaceous beds and the intimate association with effusive rocks indicate that these rocks are tuffs.

Although it contains much massive greenstone like that in the Blue Ridge, most of the Catoctin formation in the Piedmont, especially southeast of Rockfish River, is represented by chlorite and actinolite schists and phyllites. Whereas in the Piedmont these schistose rocks are distributed regionally, in the Blue Ridge they form narrow belts along thrust faults and steeply dipping, locally overturned contacts with the basement complex or highly competent, massive beds of conglomeratic graywackes, so that here, at least, the foliated metavolcanic rock is attributable to localized shear. Quartz veins that contain some chalcopyrite and copper were formed probably by tectonic desilication of greenstone where it was milled or kneaded along unyielding rock.

The chlorite and actinolite schists and phyllites in the Catoctin are uniformly fine-grained rocks in which the principal minerals are lineated in the cleavage planes approximately perpendicular to the strike. Although these rocks appear to be monomineralic in the field, thin sections reveal a mineral assemblage consisting of 50 per cent actinolite or chlorite or a combination of these minerals and 50 per cent quartz and feldspar in equal amounts. There are also small amounts of epidote, clinozoisite, magnetite or ilmenite, and leucoxene. The feldspar consists of twinned and untwinned, neomineralic and relic grains of microscopic size. The neomineralic feldspar includes albite (An10) and oligoclase (An20) in undetermined proportions. Scant relic grains of feldspar, largely replaced by secondary minerals, are identified as andesine (An40).

The massive greenstones in the Swift Run, Catoctin and Unicoi formations, while unquestionably metavolcanic rocks of basaltic or andesitic composition, are so fine-grained and extensively altered by secondary minerals that the primary (orthomagmatic) mineralogy is masked or destroyed (Pl. 2). They are green, fine-grained, massive rocks in which the minerals are not distinguishable in hand specimens. In a few places the rock contains inconspicuous altered phenocrysts of feldspar up to 0.5 inch long. Amygdules are in widely scattered exposures and cannot be used for mapping purposes. Most contain quartz, pink potash feldspar, and epidote, but some contain chalcopyrite, copper, calcite, and zeolite. In one thin section of a specimen out of the metavolcanics in the Unicoi formation, the amygdules contain spherulitic glass. Quartz, pink potash feldspar, and epidote also fill some fractures. While some of these bodies are veins, many are irregularly shaped masses, and some are breccia fillings. These brecciated zones are not traceable beyond the confines of a single exposure where they are inclosed by unshattered greenstone, but, because of the nature of the cementing material and the absence of continuity indicative of tectonic deformation, they are believed to be flow breccias.

PLATE 4.—CLEAVAGE

FIGURE 1.—Close-spaced thrust faults (1), fracture cleavage or tension joints (2), and mimetic or bedding plane cleavage (3) in the Harpers formation on United States Highway 60 east of Buena Vista, Virginia

FIGURE 2.—"Thrust" cleavage across a syncline in the Unicoi formation near the basement complex on Blue Ridge Parkway about 4 miles northeast of Humphrey Gap

Thin sections of greenstone reveal a microscopic aggregate of secondary minerals including albite (An10), quartz, chlorite, epidote, serpentine, sericite, clinozoisite (?), potash feldspar, calcite, ilmenite, and leucoxene in variable proportions (Pl. 2). Generally an ophitic assemblage of feldspar laths about 0.03 mm long is distinctly preserved. The feldspar is extensively altered, but some laths have twin lamellae with an extinction angle and a refractive index indicative of andesine (An40). The primary interstitial substance is indeterminate; in a few thin sections the interstices contain tiny remnants of a highly birefringent mineral with intermediate relief that suggests a pyroxene or amphibole. These remnants are so scant and so small that cleavage cannot be ascertained nor can they be effectively oriented with the universal stage. In the interstices of some specimens shreds of a mineral were indefinitely identified as biotite. While these occurrences provide only inconclusive evidence to identify the mafic minerals in the primary rock, some less-altered, presumably genetically related effusives in the Swift Run and Unicoi formations do contain interstitial biotite, augite, and glass.

TABLE 2.—CHEMICAL ANALYSES OF SPILITES

Constituent	1	2
SiO_2	51.22	51.08
TiO_2	3.32	2.67
Al_2O_3	13.66	11.37
Fe_2O_3	2.84	11.17
FeO	9.20	5.64
MnO	0.25	0.22
MgO	4.55	3.96
CaO	6.89	5.20
Na_2O	4.93	5.54
K_2O	0.75	1.50
H_2O	1.88	1.50
P_2O_5	0.29	0.39
CO_2	0.94	—
Total.....	100.72	100.24

1. Average of 19 analyses of spilite (Sundius, 1930, p. 9)

2. Catoctin greenstone in northern Virginia (Keith, 1894, p. 305)

Keith (1894, p. 302–309) identified metamorphosed rhyolite, andesite, and basalt in the Catoctin formation in northern Virginia. In central Virginia the greenstone is altered so that the exact classification of the primary rock is uncertain. It is primarily a basaltic or andesitic volcanic rock in which andesine (An40) is an orthomagmatic mineral replaced by albite and other secondary minerals.

The Catoctin greenstone is evidently a spilite. It was formed from a primary rock characteristic of the spilite-keratophyre association (Turner and Verhoogen, 1951, p. 201–212) and contains the same assemblage of secondary minerals with the same relations as do spilites in other regions (Gilluly, 1935, p. 225–252). A chemical analysis of a sample of Catoctin greenstone is comparable to the average chemical analysis of spilite (Table 2).

The greenstone occurs in a gradational sequence of overlapping formations that extend upward to include a great thickness of formations of Paleozoic age, indicating a geosynclinial environment at the time of extrusion similar to that of spilites elsewhere in the world (Turner and Verhoogen, 1951, p. 201–202).

If the Catoctin greenstone is a spilite, the cause of the secondary mineralization is more apparent than it is in some spilites (Gilluly, 1935, p. 336–348). The albite clearly replaces andesine (An40) and does not suggest an orthomagmatic origin. In granitic rocks in the basement complex between the Piedmont and Blue Ridge belts of the Catoctin in the limbs of a great anticlinal fold as well as in smaller anticlinal folds, dikes of greenstone cannot be analytically distinguished from the greenstones in the flows (Pl. 2). These dikes probably represent a fissure system that supplied the flows, considering that they are absent in any rocks younger than the flows and recognizing the exposure of a dike feeding into a flow at the base of the Unicoi formation in James River gorge on U. S. Highway 501 about 2.5 miles west of Snowden Post Office. The greenstone in dikes in much older plutonic rocks could not have been altered by solutions enriched in sodium from sea waters as has been suggested (Gilluly, 1935, p. 345). The secondary alteration was caused by solutions derived from the magma that supplied the primary constituents, and was essentially deuteric.

Basic intrusives.—Greenstone, metagabbro (amphibolite on the Geologic Map of Virginia, 1928), and soapstone form many intrusives, some of which are as much as several miles long and several hundred feet thick, in the Lynchburg formation and basement complex in the great anticlinal fold between the two main belts of the Catoctin formation in central Virginia. While the greenstone dikes are restricted to the northwest and the soapstone to the southeast, the metagabbro intrusives are most numerous and largest in a district about 5 miles wide roughly bisected by the contact between the basement complex and the Lynchburg gneiss (Pl. 1). Most of these intrusives are dikes, but some metagabbro and possibly some soapstone are in sills in the Lynchburg. The best exposure of such a body is in a road cut on the eastern outskirts of Madison Heights, Virginia. Another body of this type may be represented by the large mass of metagabbro between Elmington and Rockfish in Nelson County.

Like the greenstone in the Catoctin formation, the metagabbro and soapstone (Burfoot, 1930, p. 805–826; Hess, 1933, p. 377–408) are altered so extensively by secondary minerals that the primary minerals have been almost obliterated. Both the metagabbro and soapstone are medium- to coarse-grained, crudely foliated to massive rocks. The metagabbro is most extensively a black to dark-green rock of randomly oriented elongated grains of hornblende and granoblastic grains of feldspar and quartz. Along the walls of large dikes and throughout small dikes in Lynchburg gneiss, the hornblende is preferentially oriented approximately parallel to the strike of the foliation.

Thin sections of metagabbro reveal 50 or more per cent green hornblende and about 50 per cent or less feldspar and quartz. The feldspar, much of it untwinned, is crystalloblastic oligoclase (An20) except for scant grains of relic andesine (An40). Crystalloblastic quartz constitutes about 10–15 per cent of the rock, and other minerals present in minor amounts include epidote, clinozoisite (?), chlorite, calcite, ilemnite, and leucoxene.

The soapstone (Hess, 1933, p. 377–408) is a gray to green rock that appears coarse-grained in the field and fine-grained in thin sections because the outline of ghost crystals is more obvious in hand specimens, especially on slightly weathered surfaces. Talc (probably in part pyrophyllite) predominates in the soapstone, which also contains chlorite, epidote, clinozoisite (?), calcite, pyritiferous sulfides, ilmenite, leucoxene, and other minerals.

The basic dike and sill rocks in central Virginia are too altered to permit exact primary classification, but scant relic minerals, character of the secondary minerals, and the geologic occurrence indicate compositions ranging from andesitic in the greenstones through gabbroic in the metagabbros to peridotitic in the soapstones (Burfoot, 1930, p. 809–810; Hess, 1933, p. 377–408). In some dikes traced along the strike all these rock types are integrated in a way that indicates a common magmatic source. The regional distribution, relations, and parallelism of the dikes support this conclusion. Why the dikes generally parallel the regional trend and become more basic from west to east can only be speculative. The basic intrusives occur within the span of about 20 miles across which the Lynchburg formation overlaps until it disappears in the Blue Ridge. In this distance the Lynchburg thickens considerably judging from an outcrop width of about 4.5 miles in the Piedmont (Pl. 1). During deposition of the Lynchburg, the Precambrian erosion surface upon the basement complex must have subsided some hundreds or thousands of feet, tilting on a provincial scale as defined by the east-west overlap of the Lynchburg formation. This geosynclinal downwarp may have been accompanied by the formation of vertical fractures extending into the subcrust approximately parallel to the warp axis. Magma in the subcrust, differentiated into an upper layer of andesite, an intermediate layer of basalt, and a lower layer of peridotite, may have been mobilized by warping and changing crustal pressures to ascend the fractures. Where the Lynchburg is thickest the warp was greatest and fractures penetrated deepest into the subcrust so that the dike rock is more basic than where the Lynchburg is thinner. However, perhaps andesitic rock in such dikes grades downward into a gabbroic rock which in turn grades downward into a peridotitic rock so that the composition varies with the depth of erosion.

Cambrian

Chilhowee group.—This group, named by Safford (1856, p. 152–153) from exposures in Chilhowee Mountain in east-central Tennessee, includes several thousand feet of Early Cambrian clastic rocks that overlie the Late Precambrian Ocoee series (King, 1949a, p. 622–638) and underlie the Early Cambrian Shady dolomite. Beneath this dolomite or a remarkably similar equivalent formation from Alabama into Pennsylvania, there is a sequence of clastic formations composed of facies similar to those in the Chilhowee. King (1949a, p. 518–525; 1950b, p. 14–15) recommends use of the name Chilhowee group for these Early Cambrian clastic formations (Figs. 2, 3) along the length of the Blue Ridge despite the long-established use of different sets of formation names from place to place (Table 1).

A study of sections along the Blue Ridge between east-central Tennessee and Potomac River and the detailed mapping of about 50 miles from southwest of James River to Rockfish Gap in central Virginia reveal an assemblage of facies in the Chilhowee group that vary in kind and quantity horizontally and vertically from northeast to southwest (King, 1949a, p. 520–522) and from northwest to southeast (Fig. 4; Pl. 1). Northeastward the group thins, and the mapping units are distinctive and individually more homogeneous. Southeastward across the strike, although interrupted by thrust faults, the Chilhowee thickens and the separate formations are less distinctive. The Chilhowee group, like the Late Precambrian formations, is an assemblage of facies and lithologies that overlaps from east to west. These clastic rocks are in the transition zone between the Appalachian miogeosyncline to the northwest and a eugeosyncline to the southeast (Kay, 1947, p. 129; King, 1949a, p. 521, 634). The formations cannot be defined and correlated in detail from district to district. In central Virginia lithologic characteristics resemble formations in southwest Virginia, Tennessee, and northern Virginia. For example, the rocks beneath a well-defined development of the Antietam formation in central Virginia are mapped as Erwin in southwest Virginia. In central Virginia, however, this Erwin sequence is included in the Harpers formation. Also, the Harpers in this region is not underlain by a mappable mass of Weverton quartzite as in the north, but by a heterogeneous formation of interbedded Weverton-like quartzite, subgraywackes, graywackes, and volcanics. Because this formation cannot be separated into the Weverton and Loudoun formations (Table 1) and because of its position and gross lithology, the name Unicoi is used, although it is not precisely equivalent to the formation in southwest Virginia.

Unicoi formation.—From Roanoke, Virginia, into northeastern Tennessee the lower part of the Chilhowee group is mapped as the Unicoi formation, named by Keith (M. R. Campbell, 1899, p. 3) for exposures in Unicoi County, Tennessee. Northeast of Roanoke the lower part of the Chilhowee is separated into the Loudoun formation below and the Weverton formation above (Butts, 1940, p. 26–36). In central Virginia, 50 miles northeast of Roanoke, these formations are indistinguishable, and the lower part of the Chilhowee group is mapped as the Unicoi formation. This formation conformably underlies the Harpers formation in central Virginia and owing to overlap overlies the Late Precambrian and basement complex formations. The writers believe this overlap is due to subsidence during the formation of the Late Precambrian and the Chilhowee sequences, whereas King (1949a, p. 526–528; 1950b, p. 13–14) and Stose and Stose (1949, p. 311–315) recognize an angular unconformity. In central Virginia, there is continuity above the basement complex (Table 1) from the Valley and Ridge across the Blue Ridge, deep into the Piedmont province, and the Unicoi greenstones represent a final surge of Catoctin vulcanism (Bloomer, 1950, p. 753–783).

The formation consists of about 500 feet of volcanics and intergradational conglomeratic graywackes, subgraywackes, pebbly arkoses, and pebbly quartzites well displayed in sections in James River gorge along U. S. Highway 501 and on the secondary road between Buena Vista and Robinson Gap. Other less accessible sections are well exposed along creeks in the northwest flanks of the Blue Ridge.

Graywacke conglomerate (Figs. 3, 4; Pl. 3) forms the lowermost 100 feet or more, grading

downward through several feet of a Precambrian or Early Cambrian saprolite into the plutonic rock where the formation rests on the granitic basement complex. Above this saprolitic zone or where the Unicoi overlies Catoctin greenstone the graywacke consists of well-rounded clasts of granite, quartz, and feldspar 0.5–10 inches in diameter contained in a poorly graded, coarse-grained matrix of quartz, feldspar, chlorite, sericite, and iron oxide (Figs. 2, 3). Heavy minerals include ilmenite, rutile, apatite, sphene, tourmaline, and zircon. Although most of these minerals are sparsely disseminated, they are concentrated in titaniferous sandstone beds 1 inch thick interbedded in 10 feet of graywacke at the base of the Unicoi 2 miles west of Robinson Gap (Bloomer and DeWitt, 1941, p. 745–747).

The volcanics in the Unicoi include reddish-brown tuff and some greenstone and basalt that form a 4–30 foot thick member in the base of the formation. The Unicoi tuff is petrographically indistinguishable from the tuff in the Swift Run and Catoctin formations and is well exposed in Humphrey Gap where the Blue Ridge Parkway intersects U. S. Highway 60 and on Virginia Highway 56, a mile west of Tye River Gap (Pl. 1).

The greenstone is interbedded with tuff and is discontinuous along the strike. It is analytically (thin sections, spectro-analyses) indistinguishable from the spilitic Catoctin greenstone (Pl. 2). Exposures are accessible on Virginia Highway 130 about a mile east of the junction with U. S. Highway 501 in James River gorge and on Virginia Highway 56 about a mile west of Tye River Gap.

The Unicoi basalt is a gray to black, amygdaloidal rock locally interbedded in the tuff. It occurs in beds 1–10 feet thick and consists of microscopic laths of andesine (An40) in an ophitic fabric, with interstices containing glass, tiny grains of diopside or augite, and bits of biotite. It contains secondary minerals and grades into greenstone like that in the Catoctin.

The subgraywacke composing 50 per cent of the Unicoi is a gray, black, or green siltstone of subrounded and angular grains predominantly quartz with some sericitized feldspar in a matrix of chlorite, sericite, and iron oxide (Figs. 2, 3; Pl. 3). This rock resembles the subgraywacke in the Harpers formation, and some of it megascopically resembles greenstone. It contains sparsely scattered quartz pebbles up to 0.25 inch in diameter and lenticular beds of pebble conglomerate at intervals. These features are distinctive and useful in mapping.

Pebbly quartzite occurs in lenticular members 4–50 feet thick in the subgraywacke and graywacke throughout all but the lowermost 10 feet or so of the Unicoi. It consists of quartz in a coarsely arenaceous matrix and in rounded, almost spherical, white, greenish, and reddish pebbles about 0.5 inch in diameter. Pink and green feldspar is scant in the uppermost beds but conspicuous lower in the formation.

The Unicoi is only incipiently metamorphosed except locally in small, overturned folds and in shear zones between close-spaced, thrust faults (Pl. 1). Some of the quartzites and arkosites along fold axes contain crystalloblastic quartz, and the subgraywackes in the shear zones are greenschist-facies phyllites containing crystalloblastic sericite and rare grains of neomineralic oligoclase (An20) and biotite.

Harpers formation.—The Harpers formation, named by Keith (Williams and Clark, 1893, p. 68) for exposures on Potomac River near Harpers Ferry, West Virginia, is in the middle of the Chilhowee group between the conformably underlying Weverton quartzite, or Unicoi, in central Virginia, and the conformably overlying Antietam quartzite (Table 1).

The Hampton of southwestern Virginia and Tennessee and the Harpers are regarded as equivalent formations (Butts, 1940, p. 26, 36–38; King, 1949a, p. 519; Stose and Stose, 1949, p. 303). Reconnaissance indicates these formations are not exactly equivalent, but that the Harpers is partly equivalent to the Erwin which overlies the Hampton (Table 1). The base of the fossiliferous Shady-Tomstown dolomite presumably forms a horizon that defines the top of the Chilhowee group everywhere (King, 1950b, p. 23). Thicknesses estimated below this horizon indicate the Antietam quartzite is thinner than the Erwin. Thus the Harpers below the Antietam is higher in section than the top of the Hampton below the Erwin. Also much of the Harpers resembles the Erwin in appearance. This similarity is persistent in

the upper part of the Harpers from James River to Potomac River and in some sections (U. S. Highway 60) it extends to the base of the formation.

The Harpers is transitional between the heterogeneous Unicoi formation below and the homogeneous Antietam quartzite above (Pl. 3). It consists of several hundred to more than 1000 feet of fine-grained subgraywacke interbedded irregularly with quartzite. Subgraywacke predominates in the southeastern flanks and in the lower part of sections in the northwestern flanks of the Blue Ridge. Between U. S. Highway 60 and Bennetts Creek (Pl. 1), in the northwestern flanks, quartzite is dominant in the lower part of the formation.

The contact of the Harpers with the Antietam quartzite is lithologically sharply defined. The lower contact, not everywhere so well defined, is drawn at the top of the uppermost pebble conglomerate in the Unicoi formation. In many sections this conglomerate is a white or gray quartzite 4–50 feet thick that forms conspicuous ledges. In some sections, however, it is only about a foot thick and consists of well-rounded, nearly spherical pebbles of quartz in a subgraywacke matrix. Interbedded with this conglomerate and below it in the upper part of the Unicoi, there is subgraywacke so much like that in the Harpers that without pebbles the formations cannot be distinguished (Pl. 3).

This subgraywacke (Figs. 2, 3) is a gray or green, thin-bedded, locally laminated siltstone consisting of subrounded and angular grains in a fine-grained, micaceous matrix (Pl. 3). The finely arenaceous grains comprise about 50 per cent of the rock and include 90 per cent or more quartz, 10 per cent or less potash feldspar, and minute amounts of ilmenite, rutile, pyrite, sphene, tourmaline, and zircon. The matrix is composed of an aggregate of sericite, chlorite, and iron oxide. Some of the iron oxide is in minute flakes of specularite, which is concentrated in filmlike layers in the laminated variety of the subgraywacke.

The quartzite in the Harpers forms lenses, beds, and members from a fraction of an inch to 50 feet thick. In the upper part of the formation about 75 per cent of the rock is quartzite, whereas in the lower part of some sections only about 0–10 per cent is quartzite. Where the quartzite is most abundant it forms beds that average about 1 foot thick separated by layers of laminated subgraywacke that average about 3 inches thick. Below this more quartzose part the average thickness of beds and relative amount of quartzite diminish until the rock is present in lentils and widely dispersed beds only a few inches thick.

The quartzite in the Harpers is uniformly fine-grained with rounded, subrounded, and angular grains in a matrix of silica (Pl. 3). Except for rare grains of potash feldspar, tourmaline, zircon, rutile, and ilmenite, these quartzites are composed of quartz grains coated with a film of iron oxide (Pl. 3). Where this iron oxide is absent or scant above the lowermost part of the formation, the rock is white, yellowish, or bluish gray, but where it is more abundant in the lower part of the formation the quartzite is dark gray, black, or reddish brown.

Three distinctive quartzite members are separated by 100–300 feet from the top and bottom of the formation and from each other. From the uppermost downward, these members are about 25, 30, and 50 feet thick. They are recognizable in well-exposed sections, as in James River gorge and on U. S. Highway 60, but in areal mapping only the lower member is distinguished because of its greater thickness and *Scolithus* sp. unknown in other beds or members. For this unit the name Snowden member is proposed from an exposure on U. S. Highway 501 in James River gorge about 0.2 mile west of Snowden Post Office, Amherst County, Virginia (Pl. 1).

In the northwestern flanks of the Blue Ridge the Harpers subgraywacke and quartzite, except where mylonitized, are only incipiently metamorphosed. The most highly quartzose rocks are siliceous sandstones or orthoquartzites in which the only indications of recrystallization are poorly defined grain elongations and scant sutured grain boundaries. Where the Harpers is mylonitized in the northwestern flanks and especially in the southeastern flanks of the Blue Ridge, the quartzites are very much sheared, in places transformed to veinlike masses, and the subgraywackes are represented by slates and phyllites. These foliated rocks contain abundant sericite and chlorite and some crystalloblastic oligoclase (An20) and

biotite. Oligoclase was evidently the first and only feldspar formed since, in the Bluff Mountain district (Pl. 1), the formations can be traced around a syncline which contains unmetamorphosed subgraywacke in the northwest limb and phyllite in the overturned, southeastern limb. No albite is in this metamorphic progression, and biotite and oligoclase formed in small amounts during the initial stage of neomineralization. The close association of the crystalloblastic rock with the overturned limb of the fold and elsewhere the association of such rocks with thrust faults are evidence of the genetic relationship of the metamorphism and structural deformation.

Antietam quartzite.—This formation was named by Keith (Williams and Clark, 1893, p. 68) for exposures near Antietam Creek, Maryland. It consists of about 600 feet of quartzite, in the upper part of the Chilhowee group, conformably above the Harpers formation and below Tomstown dolomite (Pl. 1). It forms the bold, hog-backlike northwestern front of the Blue Ridge and supplies a great sheet of bouldery wash that spreads from the lower part of the northwestern slope of the Blue Ridge far into the Valley and Ridge province (King, 1950b, p. 58–63). This wash mantles the outcrop belt of the Tomstown dolomite and the upper part of the Antietam and obscures the boundary between the two. James River and a few of the westward-flowing streams out of the Blue Ridge have penetrated the wash and exposed the bedrock. Particularly around the southwestern end of Sallings Mountain (Pl. 1), the contact of the Antietam and Tomstown is clearly revealed as a transition zone consisting of about 25 feet of dolomitic sandstone. The lower contact of the Antietam is well exposed and sharply defined and can be accurately mapped.

Although some workers (Butts, 1940, p. 26, p. 38–40; King, 1949a, p. 519; Stose and Stose, 1949, p. 303) consider the Antietam equivalent to the Erwin formation (Table 1), the writers believe these formations are only partly equivalent and that part of the unit mapped as Harpers is equivalent to the Erwin (Fig. 4).

The Antietam is a homogeneous, locally cross-bedded, uniformly arenaceous, white to bluish-gray, siliceous sandstone or orthoquartzite (Fig. 2) in beds 1–20 feet thick. The sorting is so nearly complete that the arenaceous, rounded to subangular grains are 99 per cent or more quartz and less than 1 per cent potash feldspar, rutile, ilmenite, tourmaline, and zircon (Fig. 3). This uniformity is relieved by (1) the sporadic occurrence of nearly spherical pebbles of quartz in small lenses, (2) clayey partings 1–2 inches thick between some of the thick beds in the basal part of the formation, (3) a small amount of carbonate intermixed with the silica matrix in the uppermost part of the formation, and (4) microscopic films of iron oxide on some grains (Pl. 3).

The only fossil the writers found in the Antietam is *Scolithus linearis* (James, 1892, p. 32–44; Fenton and Fenton, 1934, p. 341–348). Butts (1940, Pt. 1, p. 40) says there are fragments of *Olenellus* sp. and *Obelella* sp. in the rusty layers between some of the quartzite beds, but he does not name a locality.

About 4 miles southwest of Natural Bridge Station Walcott (1892, p. 52–53), accompanied by Willis and H. D. Campbell, collected *Olenellus thompsoni*, *Hyolithus americanus*, and *H. communis* in a "calcareous sandstone" then regarded as part of a formation (Potsdam) later defined as the Antietam. However, the rock in the locality denoted by Walcott is in the upper part of the Rome-Waynesboro formation which overlies the Tomstown, and the Antietam is absent from the section because of thrust faulting. In east-central Tennessee *Olenellus* sp. has been found in the Murray shale (King, 1949a, p. 520) which is partly equivalent to the Harpers formation, and in Maryland diagnostic Lower Cambrian trilobites are found in the Antietam (Amsden, 1951, p. 102).

Tomstown dolomite.—Stose (1906, p. 208) named this 1000 feet of pure dolomite for exposures near Tomstown, Franklin County, Pennsylvania. It is equivalent to the Early Cambrian Shady dolomite (Butts, 1940, p. 40–56) of Tennessee and southwest Virginia and is oldest in a vastly thick succession of Cambrian and Ordovician carbonate rocks and shales exposed across the Valley and Ridge province (Butts, 1933).

In central Virginia where the contacts are locally exposed the Tomstown grades downward through about 25 feet of dolomitic sandstone

into the siliceous sandstone or orthoquartzite of the Antietam formation and upward into the Rome-Waynesboro formation through an unknown thickness of impure dolomite and dolomitic limestone. The upper boundary is drawn at the top of the first bed of pure dolomite encountered below the lowest red shale of the Rome-Waynesboro formation.

The formation is important insofar as it conformably overlies and defines the upper limit of the Chilhowee group, and its outcrop belt spans the boundary between the Blue Ridge and Valley and Ridge provinces.

Late Precambrian and Lower Cambrian Stratigraphic Relations

General statement.—King (1949a, p. 526–528, 635; 1950b, p. 13–14) and Stose and Stose (1949, p. 311–315) recognize an unconformity between the Catoctin greenstone and the Chilhowee group, and they believe the sediments above and below this unconformity came from geographically different sources. They conclude that the formations below the unconformity are Late Precambrian and those above are Early Cambrian. The writers cannot recognize this unconformity and conclude there is an uninterrupted sequence of formations above the "early" Precambrian basement complex (Bloomer, 1950, p. 753–783). Bloomer and Bloomer (1947, p. 104–105) define the formations below the Unicoi and above the basement as Early Cambrian. Cloos (1951, p. 27) assigns the Catoctin to the Early Cambrian because its cleavage and other minor structures are similar to those in Early Cambrian rocks.

Age assignment of the formations is not so important as is the determination of their interprovincial and geotectonic relations. Thus an angular unconformity between the so-called Late Precambrian and Early Cambrian formations and the presumption that Chilhowee sediments were derived from the east and not from the west like the underlying formations isolate the eugeosynclinal basin (Piedmont geosyncline) from the Paleozoic miogeosynclinal basin (Appalachian geosyncline) and leave in doubt the correlation of the Evington group (Brown, 1953, p. 90–96) or so-called Wissahickon complex (Geologic Map of Virginia, 1928), the Catoctin greenstone, and the Lynchburg formation in the Piedmont (Pl. 1). But if no unconformity exists and if the eastern and western basins are integrated parts of the same geogynclinal system, perhaps the Late Precambrian-Early Cambrian boundary is only arbitrary.

Some workers find the volcanics of the region a suitable basis of demarcation between the Precambrian and Cambrian formations, while others believe these rocks indicate stratigraphic continuity of the section (Bloomer and Bloomer, 1947). They are not necessarily stratigraphically persistent because through some thousands of feet the spread of the successive volcanic flows may vary widely, and where supplied from extensively dispersed fissures, volcanics such as those in the Swift Run, Catoctin, and Unicoi formations have an irregular vertical and lateral distribution.

Regional relations.—The Chilhowee formations consist of clastic sediments that vary in kind, proportion, and interrelationships in three dimensions (Fig. 4). These formations are distinguished by lithology and relative position in the stratigraphic succession (Table 1). While the Chilhowee is variable in character and thickness along the Blue Ridge it is conformably overlain by the Tomstown-Shady dolomite varying little in lithology and containing fossils that establish its age within narrow limits (Butts, 1940, p. 40–56; King, 1950b, p. 23).

The angular unconformity recognized by King (1949a, p. 526–528, 635; 1950b, p. 13–14, 24–25) and Stose and Stose (1949, p. 311–315) between the Late Precambrian and Early Cambrian separates the Chilhowee group from the Ocoee series in Tennessee, from the Mount Rogers volcanics in southwestern Virginia, and from the Catoctin greenstone in northern Virginia. In central Virginia the Chilhowee and Catoctin greenstone are conformable and intimately related by intertonguing near the overlap margin of the older formation. Beyond this margin the Chilhowee group unconformably overlies the basement complex.

In addition to the evidence provided by the unconformity in question, King (1949a, p. 625–630) and Stose and Stose (1949, p. 307–308) believe the Chilhowee group is not in continuous sequence with the older Late Precambrian formations because of differences in the respective

characteristics, attributed to differences in the direction of the sources of the sediments. While the writers believe the Late Precambrian formations are older and agree that the sediments differ from those in the Chilhowee, they do not believe the difference in age is any greater than it is within the succession of units above or below the disputed unconformity or that the difference in character is indicative of a significant difference in the source of sediments and hence in the age of the formations.

Mapping (Fig. 4; Pl. 1) of these Late Precambrian and Early Cambrian clastic and volcanic rocks shows an overlapping assemblage that thickens and becomes less heterogeneous from west to east into a geosynclinal basin. The source of the detritus is the basement complex, which was mantled by as much as 100 feet of saprolitic regolith before subsidence. During the initial geosynclinal subsidence much subgraywacke (Lynchburg formation) was deposited upon a thin layer of conglomeratic graywacke. Following extensive vulcanism along the margin of the basin the rate of subsidence decreased, and the overlap margin advanced westward so that the marginal facies were reworked and sorted. The Chilhowee group is such a marginal assemblage, which thins and becomes more quartzose to the west until it finally disappears. After deposition of the Chilhowee the subsidence probably increased laterally and depositional conditions stabilized enough to permit widespread accumulation of the Tomstown-Shady dolomite.

In the Piedmont province east of the Blue Ridge a great expanse of clastic rocks now represented by the phyllites and schists of the Evington group (Brown, 1953, p. 90–96) is believed to conformably overlie the Catoctin. These rocks are partly equivalent to the Chilhowee group and probably to some of the younger carbonate rocks and shales in the Valley and Ridge province (Fig. 4, Pl. 1). Some of the carbonate rocks and shales in the Valley and Ridge province grade eastward into metamorphosed clastic rocks, and the Blue Ridge lies along the boundary zone between a deeper geosynclinal basin to the east that contains clastic sediments and a shallower geosynclinal basin to the west that lacks the older formations and contains much carbonate rock and shale. Thus, Late Precambrian formations and the Early Cambrian Chilhowee group are believed to be an overlapping succession of units that lie across the ancestral Blue Ridge undation that separated an eastward eugeosynclinal basin from a westward miogeosynclinal basin.

Triassic

Diabase dikes 1–100 feet thick and up to several miles long that trend in all directions intrude the bedrock formations in the Piedmont, Blue Ridge, and Valley and Ridge provinces (Pl. 1). These Triassic dikes (Geologic Map of Virginia, 1928; Butts, 1933) are more numerous and larger in the Piedmont than in the other provinces in central Virginia. They consist of labradorite (An50) in a uniformly fine-grained, ophitic fabric with augite and olivine in the interstices. Some specimens contain andesine (An40) and accessory quartz associated with augite.

Quaternary

Mountain wash.–The bedrock is mantled by mountain wash, floodplain and terrace alluvium, and upland gravel probably no older than Pleistocene (Pl. 1; King, 1949a; 1950b, p. 58–63). The mountain wash is most extensive along the northwestern front of the Blue Ridge where it forms piedmont fans as much as 3 miles wide and 100 or more feet thick composed of crudely stratified, bouldery gravel derived from Antietam quartzite. Along the upper margin of these fans manganese oxide, limonite, and bauxite occur in the saprolite from Tomstown dolomite (King, 1950b, p. 54–57). These have not been exploited recently.

No such fans are formed along the southeastern flanks. Instead there are pedimentlike benches or dissected strath levels, well above stream levels that slope gently southeastward (White, 1953, p. 561–580). These benches are veneered by not more than about 10 feet of bouldery wash derived from the basement complex and Catoctin greenstone from within the Blue Ridge.

Floodplains.—The main streams have developed narrow, discontinuous floodplains and floodplain terraces. However, where Tye River

and Rockfish River emerge from the main mass of the Blue Ridge, each flows in a broad floodplain or alluvial plain that is topographically unconformable. Downstream from these plains, the floodplain development is much less pronounced. Unconformity is due to the bedrock geology since the boundaries of alluvial plains coincide with the contacts of the Marshall formation and the more resistant Pedlar formation and Lovingston gneiss (Pl. 1). Everywhere along the southeastern front of the Blue Ridge and the northwestern margin of the Piedmont the topography reflects bedrock variations.

Upland gravel.—Upland gravel mantles broad interstream areas in the Piedmont and Valley and Ridge away from the Blue Ridge. These crudely stratified cobbly gravels consist of quartzite in both provinces. In the Valley and Ridge some of this quartzite may have come from Silurian formations and some from the Chilhowee group, but in the Piedmont its origin is unclear. While some of it might have been derived from the Lynchburg or other Piedmont formations, much of it resembles Antietam quartzite, and some of the cobbles contain *Scolithus* sp. If some is derived from the Chilhowee, topography and location of exposure belts of the Chilhowee must have changed since the gravel was deposited because the mantle of Chilhowee quartzite fragments in the Piedmont is impossible as relations are at present (Pl. 1). If the gravels are composed partly of Chilhowee quartzite and are Pleistocene, perhaps they indicate a peneplainlike erosion surface across the three physiographic provinces in central Virginia. On such a surface, a mantle of quartzite gravel might spread some tens of miles from the source area.

Structure

General Statement

The principal structural features in central Virginia are the Catoctin Mountain-Blue Ridge anticlinorium, the Buena Vista anticline, and a zone of faults by which one of these folds has been thrust upon the other so that any intervening fold or folds are not well defined (Pl. 1). Beyond the northeastern and southwestern extremities of the Buena Vista anticline and the area mapped, the rocks of the Blue Ridge are thrust-faulted upon the carbonate rocks and shales of the Valley and Ridge province.

Lesser or minor structural features include intricate folding that seems to be intraformational, rock-cleavage, foliation, lineation, and strike-slip or transverse faults.

Catoctin Mountain-Blue Ridge Anticlinorium

The Catoctin Mountain-Blue Ridge anticlinorium in central Virginia spans more than 25 miles from the northwestern flanks of the Blue Ridge into the Piedmont province (Fig. 1; Pl. 1). According to Jonas (1929, p. 507–509) and Jonas and Stose (1939, p. 576–579), both limbs are faulted obscuring the width and relationship to contiguous folds. Bloomer (1950, p. 764–765) and the writers, however, find no evidence of faults large enough to isolate the anticlinorium n ce ntral Virginia (Pl. 1).

The southeastern limb is defined by the axis of the James River synclinorium (Brown, 1953, p. 92–94) and contains the Lynchburg formation, Catoctin greenstone, and Evington group. Its conspicuous foliation and its bedding are essentially parallel and dip steeply southeastward except in Madison Heights where the Lynchburg formation is displayed in open folds, some of which are nearly symmetrical. Across the axes of these open folds, however, there is no significant variation in the angle or direction of dip of the foliation.

The northwestern limb of the anticlinorium contains Late Precambrian and Early Cambrian formations and is thrust-faulted (Fig. 1; Pl. 1). However, unlike Jonas and Stose (1939, p. 576–579) and Stose and Stose (1949, p. 305), the writers find no statewide thrust faults and only insignificant ones in the mid-section of the map area, so that the anticlinorium is almost intact or structurally continuous with the Buena Vista anticline and the folds in the Valley and Ridge province (Pl. 1).

In the northwestern limb the number of thrust faults and their displacement varies. At and beyond the ends of the Buena Vista anticline these faults are more numerous and of greater magnitude than they are adjacent to the main part of the anticline (Pl. 1). These relations suggest that the anticline acted as a

buttress in the northwestern limb of the anticlinorium.

Between the two limbs is a broad expanse of foliated basement rock in the middle of which is an infolded, locally faulted, isoclinal syncline of Lynchburg metasediments (Fig. 1; Pl. 1). This basement complex was foliated prior to deposition of the Precambrian basal conglomerates of the Rockfish member of the Lynchburg formation. It dips steeply southeast, and parallels the strike of the fold axes in the region. The medial isoclinal syncline parallels this alinement and has been traced at least 50 miles into northern Virginia (Gooch, Personal communication, 1952). It is about 1000 feet wide and is locally faulted along its borders with the basement rocks. A well-developed foliation all through the medial syncline is parallel to the foliation in the basement complex.

The Catoctin Mountain-Blue Ridge anticlinorium is not a typical tectonic flexure. Its amplitude is not great as indicated by infolded outliers and the consistent attitude of the foliation across the fold which spans about 28 miles. The exposure of basement rocks in the cores of some of the lesser folds in the northwestern limb and the attitude of the Buena Vista anticline do not indicate nappe-like overturning on a scale to account for the uniform dip of the foliation across the span of the anticlinorium. Hence this fold is probably an epeirogenically uplifted expanse between two great geosynclinally subsident expanses with a long and complex history. Prior to orogenic deformation the anticlinorium was the cratonic margin of the eastward geosyncline. Later it became an undation between this eastern basin and the miogeosyncline to the west. Subsequently, after the region was folded and faulted, the anticlinorium was epeirogenically uplifted with a southeastward tilt or slope. Thus it is a manifestation of an undation between geosynclinal basins, as is the overlap of Late Precambrian and Early Cambrian formations.

Buena Vista Anticline

The main mass of the Catoctin Mountain-Blue Ridge anticlinorium is separated from the Buena Vista anticline to the northwest by several faults (Pl. 1). These faults presumably caused the collapse or telescoping of a synclinal segment less than 5 miles wide between the unfaulted mass of the anticlinorium and the Buena Vista anticline which lies along the northwestern front of the Blue Ridge. The faulted segment and the Buena Vista anticline are interpreted as parts of the northwestern limb of the anticlinorium. Jonas and Stose (1939, p. 576–579) delimit the northwestern extent by a great fault which they believe thrusts basement rocks upon Late Precambrian and Early Cambrian formations in the Blue Ridge. King (1950b, p. 47–50) and the writers fail to recognize such a great fault. According to Jonas and Stose, the smaller Buena Vista anticline is of the same order of magnitude as the anticlinorium, while the writers believe it is a subordinate fold in the northwestern limb of the anticlinorial system.

From the extremities where it disappears with an average plunge of 15 degrees, the Buena Vista anticline extends about 40 miles between Arnold Valley and Big Level along the north western front of the Blue Ridge (Pl. 1). Along this front beyond the extremities of the fold the formations of the Blue Ridge are thrust faulted upon the formations of the Valley and Ridge so that certain contact and sequential relations are obscured. The Buena Vista anticline, like the Shenandoah salient in the Elkton district in northern Virginia (King, 1950b, p. 39–50), is only insignificantly faulted against the Valley and Ridge formations and the sequence in the northwestern limb is complete (Pl. 1). In this fold the Chilhowee formations are revealed farther away from the main body of the eastern geosynclinal basin than they are elsewhere between Roanoke and Elkton, Virginia (King, 1950b, p. 6–50).

The northwestern limb of the Buena Vista anticline, beginning with the unconformably underlying basement complex, contains an uninterrupted sequence of Cambrian formations. The southeastern limb is imbricated by thrust faults so that it is only partly exposed in a few places (Pl. 1). Locally the core of the anticline has been faulted so that parts of the southeastern limb or segments of other folds are thrust upon the northwestern limb.

The limbs, as observed from a distance and computed from outcrop widths, do not dip more

than 25°. As measured in outcrops, except on the extremities of the fold the dips average almost twice as much due to minor folds.

Thrust Faults

The faults in the northwestern limb of the anticlinorium overlap along the trace, disappear in the basement complex, or terminate with a gradual diminution of displacement within the overlying layered mass (Pl. 1).

Southeastward across the strike no faults of importance are known for more than 25 miles into the Piedmont province excepting the displacements along the margins of the isoclinally infolded belt of the Lynchburg formation in the basement complex (Fig. 1; Pl. 1). Toward the northwest no significant faults are known across an expanse of 3 or 4 miles between the Blue Ridge front and the Pulaski fault (Butts, 1933, map) in the Valley and Ridge province. Thus thrust faults are concentrated in the northwest limb of the Catoctin Mountain-Blue Ridge anticlinorium in central Virginia (Pl. 1). This concentration may be an imbrication due to the buttressing of orogenic thrust along the undation between the Piedmont eugeosyncline and Valley and Ridge miogeosyncline.

In this Blue Ridge fault zone, Stose and Stose (1949, p. 305, 312) recognize individual faults that extend many miles along the Blue Ridge, but the writers have not found a single fault that does not terminate in the central Virginia area and King (1950b, p. 47–50) found none that do not locally terminate in the Elkton area.

With one exception, the displacements are equivalent to the distances between fold axes in the northwestern limb, a conclusion based upon the similarity of facies in different fault blocks and map relations that permit restoration of faulted folds with some certainty. Hence the writers do not believe any of the displacements in the Blue Ridge of central Virginia are great enough to isolate structurally one part of the region from another.

There are at least two varieties of thrust faults in the Blue Ridge of central Virginia. One, more numerous than the other, dips about 30° or more and thrusts older upon younger rocks (Pl. 1). Another variety has low dips and locally thrusts younger upon older rocks (Pl. 1). The high-angle faults, presumed to be in part offshoots from the low-angle faults, have displacements of a few hundred feet and fragment but do not override folds. Among the low-angle faults the displacement probably varies considerably. Wherever younger rock is thrust upon older rock deep, close-spaced folds must have been truncated by a low-angle fault of limited displacement (Pl. 1). At least one low-angle fault in the Blue Ridge thrusts older upon younger rock and has a displacement of several miles; it is folded and slightly overturned in Sallings Mountain (Pl. 1; Bloomer, 1951, p. 640–650).

Mylonite

Between James River and U. S. Highway 60 along the southeastern-most of the Blue Ridge faults (Pl. 1), the Marshall formation in the basement complex has been pulverized and milled to form a slaty rock in a belt as much as a mile wide. This mylonite is unique in the region and Bloomer (1951, p. 640–650) attributes it to a renewal of movement after the folding of the fault. The regenerated fault was impeded by the fold, and localized mylonitization ensued.

Elsewhere in the region the graywackes, subgraywackes, and greenstones of the Swift Run, Catoctin, Unicoi, and Harpers formations, where associated with thrust faults, have been transformed to slates and phyllites, which are well displayed in the southeastern flanks of the Blue Ridge in the vicinity of James River and in the northwestern flanks from about Sherando northeastward for many miles (Pl. 1). In these sections the rocks have a cleavage that is genetically related to thrust faulting. Away from the faults this cleavage becomes less slatelike, and the recrystallization expressed mainly by sericite and chlorite disappears.

Strike-Slip Faults

Some faults oriented transversly with respect to the strike of the folds, thrust faults, and foliation of the region (Pl. 1), have nearly vertical dips and extend not more than a mile or two. While some have the map relations of tear faults, some are not associated with thrust

faults and may be flaws (Perry, 1935). In both types a prominent strike-slip component is indicated by the off-set relations. If these features are essentially strike-slip faults, they are probably in some way attributable to the northwest thrust of the region.

Normal Faults

White (1950, p. 1309–1346) projects a major normal fault along the southeastern front of the Blue Ridge which the writers cannot verify in central Virginia. Such a fault and others of the type may exist in the region, but the large dimensions of the mapping units, extensive thrust faulting, complexity of minor structural features, deep weathering, erosion, and dense brush obscure all such displacements except some defined by minor off-sets in outcrops. The southeastern front is formed along the contact of the Pedlar or Catoctin formations in the Blue Ridge with the Marshall formation in the Piedmont. There are salients, recesses, and outlying hills along the front corresponding to variations in the bedrock in a way that cannot be attributed to normal faulting.

Intraformational Folding

The dips of the limbs of large folds such as the Buena Vista anticline are clearly revealed by areal mapping (Pl. 1) and in some mountain sides viewed from a distance. These dips are not indicated by the axial planes of minor folds seen in exposures. While the Antietam quartzite and underlying formations in the northwestern limb of the Buena Vista anticline dip about 25° NW. with no large scale overturning, the minor folds, best displayed in the Harpers and Unicoi formations, have axial planes that dip southeast. If the minor folds which are extensively isoclinal and overturned are drag folds they are not normal ones. The axial planes of conjugate drag folds in the northwestern limb of the Buena Vista anticline should dip northwest, not southeast.

Because the minor folds are not genetically related to the major folds and are variably developed from one rock unit to another, they are considered intraformational folds. This does not imply primary or prediagenetic folding due to slump or flow. Contrarily, the consolidation of the rock during formation of these folds is indicated by the thickening of beds in the axial zones, well-formed boudinage, and fracture cleavage (Pl. 4). The minor folds were probably formed during an orogenic episode preceding formation of the major folds; they thickened and increased the competence of the mapping units which later were folded on the larger scale represented by the Buena Vista anticline. This must have taken place without the usual slip between beds, which may explain the brecciation of the Antietam quartzite along the contact with the underlying, intricately folded Harpers formation where differential movement may have been concentrated. Another possible effect of the multiple folding is the southeastward dipping cleavage which may have resulted from a compression that created the major folds. When these folds formed they must have had an extraordinary resistance to flexure owing to the lack of bedding planes that conformed to the contour of the developing flexure. The monoclinal cleavage which represents a shear system may have formed in place of bedding-plane slip during the shaping of the large folds.

The structural relations of the minor folds are speculative, but they seem to indicate two episodes of folding separated by an episode of thrust faulting (Bloomer, 1951, p. 640–650), as evident in the relations of the overthrust fault that forms an anticlinal arch across the Blue Ridge and encircles Sallings Mountain (Pl. 1). This fault is folded on a scale equivalent to that of the Buena Vista anticline to which its contour roughly corresponds and it displaces some small folds. The displaced folds which are discordant with folds beneath the fault block, the fault itself, and the folding of the fault, clearly indicate 3 episodes of deformation. Other faults in the area may have formed during one or more of these episodes.

Lineation

Although boudinage, crinkles, elongated pebbles, and intersecting "s" surfaces are noted from place to place, the most persistent lineation is expressed by grains of biotite, chlorite, and sericite elongated in the direction of dip approximately in the direction of the *a* fabric

axis. This lineation on thrust cleavage surfaces suggests it was caused by regional thrusting.

Cleavage

Cleavage differs in the three geological districts in central Virginia which include (1) a broad expanse of Precambrian basement rocks partly in the Blue Ridge and partly in the Piedmont, (2) a belt of Late Precambrian gneisses and schists in the Piedmont, and (3) the main mass of the Blue Ridge consisting of a variety of complexly folded and faulted formations (Pl. 1).

The basement complex consists of variously granitized formations in which there is a foliation that has been progressively obliterated in the transition from the parent rock to the "granite" (Fig. 10 Pl. 1). In the Pedlar formation the foliation is seen sporadically, while in the Lovingston gneiss it is conspicuous. Since the basement complex gneisses supplied boulders and other fragments in the Late Precambrian conglomerates of the region, the basement complex foliation is Precambrian. Southwest of the central Virginia area where the rocks are only incipiently granitized, isoclinal bedding is discernible, and the foliation has the relations and character of flow or axial plane cleavage. This cleavage dips steeply southeast and strikes northeast parallel to the fold axes and other features in Late Precambrian and Early Cambrian formations of the region. Thus the trend of the Precambrian foliation in the basement complex is clearly parallel to the structural trend of subsequently formed features.

The Late Precambrian Lynchburg and Catoctin formations in the southeastern limb of the Catoctin Mountain-Blue Ridge anticlinorium, southeast of the basement complex (Fig. 1; Pl. 1), are characterized by a southeastward dipping flow or axial plane cleavage expressed by folia of biotite, sericite, and chlorite. Particularly in the phyllites in the district, this cleavage contains tiny crinkles with unbroken axial planes that do not plainly define another cleavage. Farther southeast in the Evington group such a cleavage is well formed. In the Late Precambrian rocks the axial plane cleavage is the most conspicuous structural feature. It is nearly parallel to the bedding except locally where some small scale open folds have been observed in and near the bluffs along James River at Madison Heights (Pl. 1).

The Blue Ridge district consists of basement rocks and Late Precambrian and Early Cambrian formations, in the northwestern limb of the anticlinorium where there are three kinds of cleavage including (1) a mimetic or bedding-plane cleavage, (2) a close-spaced joint set or wide-spaced fracture cleavage, and (3) a cleavage closely related to thrust faulting (Pl. 4).

The mimetic or bedding cleavage is formed in thin layers of subgraywacke interbedded with quartzite. It is expressed by a lamination of filmlike layers composed of tiny iron oxide and sericite flakes separated by silty bands of quartz and sericite a millimeter or more thick, and it remains parallel to the bedding throughout the intraformational folds.

A fracture cleavage or close-spaced tension jointing is best developed in thin layers of quartzite interbedded with thin layers of subgraywacke. It is approximately perpendicular to bedding surfaces and is clearly the initial stage in the formation of boudinage. Where the deformation is not characterized by the thickening and thinning of the competent units or boudinage, the fracture cleavage forms smooth, uncurved surfaces with spacing in accord with the varying thicknesses of beds.

While the bedding-plane and fracture cleavages are largely confined to rock units consisting of interbedded quartzites and subgraywackes, a third type of cleavage occurs in all the rocks younger than the basement complex, excepting Triassic dikes and the Pleistocene mantle. Its classification is in doubt although it seems to be a shear cleavage. Since this term has several connotations the term "thrust" cleavage is preferred.

All this so-called thrust cleavage, regardless of folding, dips 20°–70° SE. and strikes northeast. In the subgraywackes and tuffs it is expressed by a schistosity spaced at intervals of about 1 mm (Pl. 4, fig. 2). In quartzitic rocks and coarse-grained graywackes the thrust cleavage is not expressed by mineral orientation and is spaced at intervals ranging from a fraction of an inch to several feet (Pl. 4, fig. 1). Though no displacement is evident in homogeneous rock masses, in other masses displace-

ments range from a fraction of an inch to many feet, including some that are mappable. In the basement complex this cleavage coincides with the foliation and is not distinctive. Also in the layered rocks where the limbs of minor folds dip southeastward within certain limits, the thrust cleavage coincides with the bedding-plane cleavage. Similarly the thrust cleavage in places coincides with the fracture cleavage so that minor break thrusts are formed.

The so-called thrust cleavage in the Blue Ridge district is essentially a very close-spaced imbrication of thrust faults and cannot be used to determine stratigraphic succession.

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Short Notes

AGE DETERMINATIONS ON SOME ROCKS FROM THE BOULDER BATHOLITH AND OTHER BATHOLITHS OF WESTERN MONTANA

BY RANDOLPH W. CHAPMAN, DAVID GOTTFRIED, AND CLAUDE L. WARING

Introduction

This paper presents some new age data recently obtained on rocks from the batholiths in western Montana. The Boulder batholith, a large composite intrusion composed mainly of quartz monzonite, is on the Continental Divide and covers an area of about 1200 square miles. The Philipsburg batholith is a much smaller and simpler intrusion of quartz monzonite about 50 miles west of the center of the Boulder batholith. The Idaho batholith is a huge composite body of granitic rocks, the eastern edge of which is about 100 miles west of the center of the Boulder batholith. Most of the age data presented here were obtained from the Boulder batholith, and the age of this body is now reasonably evident. The data from the Philipsburg and Idaho batholiths suggest certain time relationships between these bodies and the Boulder batholith, but more information is needed before positive conclusions can be drawn.

This study is part of a program undertaken by the U. S. Geological Survey on behalf of the Division of Research of the Atomic Energy Commission.

Montis R. Klepper supplied much of the geologic information used in dating the Boulder batholith. George H. Hayfield helped to separate the minerals and to concentrate and purify the radioactive zircon and monazite. Esper S. Larsen, Jr., Howard W. Jaffe, Lorin R. Stieff, and Thomas W. Stern offered valuable assistance and advice.

Nature and History of the Boulder Batholith

The Boulder batholith is a composite pluton consisting of quartz diorite, granodiorite, quartz monzonite, granite, alaskite, aplite, and pegmatite; quartz monzonite is by far the most abundant rock type. The relative ages of all these types have not been determined, although the alaskite, aplite, and pegmatite cut the others.

The role of the Boulder batholith in the geologic history of western Montana is fairly clear. In Late Cretaceous time a thick series of andesitic pyroclastics and flows was extruded over a wide area. Plant remains of probable Judith River age (Roland Brown, Personal communication), just slightly older than middle Late Cretaceous, have been found in pyroclastic beds high in this thick series. Near the close of the Cretaceous the pyroclastics and flows were folded and faulted by the Laramide deformation. Following this, either in very Late Cretaceous (Knopf, 1913, p. 34) or very early Tertiary time, the plutonic rocks of the Boulder batholith formed by one or more processes of uncertain nature. These plutonic rocks intruded volcanics and older rocks and extensively contact metamorphosed them. Considerably later, a variety of fairly siliceous volcanics was extruded. The oldest of these are basal tuffs with early Oligocene fossils; these tuffs rest with marked unconformity on the eroded plutonic rocks of the batholith. In part contemporaneous with the tuffs and in part somewhat later, perhaps in Oligocene or Miocene time, flows and tuffs of trachyte, rhyolite, and dacite were extruded onto a topography that had been cut on the batholith, probably during Eocene time.

From the above stratigraphic and structural relations, it can be concluded that the Boulder batholith is later than middle Late Cretaceous and pre-early Oligocene.

Method of Age Determination

The method described by Larsen *et al.* (1952) was used to determine the age of the rocks. This method is based on lead-alpha activity ratios in suitably radioactive accessory minerals, principally zircon and monazite. In both zircon and monazite the lead present is believed to be essentially radiogenic. This has been convincingly borne out by geologic evidence and, where possible, by comparison with isotopically determined ages (unpublished data by E. S. Larsen, Jr.).

The alpha activity was first determined for each radioactive accessory by a thick-source alpha-counting technique, and the lead content was then measured by a spectrographic method developed by Waring and Worthing (1953). The accuracy of the alpha-activity measurements is believed to be ±5 per cent, and the accuracy of the lead analyses 6–10 per cent.

Preparation and Processing of Samples

Chapman collected and processed the rock types. Fifty-pound samples of each were crushed and sized, and the radioactive accessories were concentrated and purified by heavy liquids, the Frantz isodynamic magnetic separator, and hand picking. Gottfried made an alpha count of each purified concentrate, and Waring determined spectrographically the amount of lead in each concentrate. The age of each mineral was then calculated from the lead-alpha activity ratio. The results are shown in Table 1.

TABLE 1.—AGE DETERMINATIONS ON MINERALS FROM BOULDER, PHILIPSBURG, AND IDAHO BATHOLITHS, MONTANA

Number	Rock	Mineral	Counts in α/mg/hr	Lead (ppm)	Age (MY)
BOULDER BATHOLITH					
52-C-45-Z	Quartz monzonite	Zircon	227	8	69
52-C-60-Z	Quartz monzonite	Zircon	203	6	71
52-C-10a-Z	Quartz monzonite	Zircon	160	4.6	69
52-C-8-Z	Alaskite	Zircon	4990	127	61
52-C-8-M	Alaskite	Monazite	6545	231	72
PHILIPSBURG BATHOLITH					
53-C-198-Z	Quartz monzonite	Zircon	858	18	50
IDAHO BATHOLITH					
53-C-210-Z	Quartz monzonite	Zircon	275	6.2	54
53-C-210-M	Quartz monzonite	Monazite	3123	79	51

52-C-45 Medium-grained porphyritic hornblende-biotite quartz monzonite with large phenocrysts of pink potash feldspar, from the quarry 1½ miles west of Boulder, Montana

52-C-60 Medium- to fine-grained hornblende-biotite quartz monzonite with more ferromagnesian minerals than in 52-C-45, from a road cut about 3 miles northeast of Elk Park, Montana

52-C-10a Medium-grained quartz monzonite with about 30 per cent biotite and hornblende, from the border of the batholith about 7 miles southeast of Helena, Montana

52-C-8 Medium-grained alaskite taken half a mile southwest of the summit of Elkhorn Peak, Montana

53-C-198 Medium-grained biotite-hornblende quartz monzonite from the Philipsburg batholith, 1 mile east of Philipsburg, Montana

53-C-210 Medium-grained white gneissoid quartz monzonite from the border zone of the Idaho batholith in Lost Horse Creek, Bitterroot Mountains, Montana

Age Relationships of the Batholiths

The ages of five rock types from the Boulder batholith were determined. These gave an average of 68 million years and suggest that the batholith was emplaced at or near the close of the Cretaceous. All five determinations fall within ±10 per cent of the average, a very close conformance for rocks so young. However, as the results are all within the limit of error of the lead-alpha activity method, no conclusions can be drawn as to the relative ages of the five rock types.

The age of 50 million years determined for the Philipsburg batholith suggests that this pluton is somewhat younger than the Boulder batholith. However, great significance should not be attached to this one determination.

A white gneissoid quartz monzonite from the Idaho batholith yielded both zircon and monazite that gave ages of 54 and 51 million years, respectively, a remarkably close agreement for two minerals with such different lead contents. Another determination, previously made by Howard W. Jaffe on a monazite from the same gneissoid quartz monzonite taken farther west along Lost Horse Creek, gave an age of 72 million years. These data suggest that this rock is at least as young as, if not somewhat younger than, the rocks of the Boulder batholith—*i.e.*, very Late Cretaceous or even early Tertiary. Age determinations previously made on certain other rocks from the Idaho batholith, however, gave an average age of 100 million years (unpublished data by Larsen, Gottfried, Jaffe), and it seems reasonably clear that the bulk of this enormous body is probably mid-Cretaceous. Thus the Idaho batholith may contain plutonic rocks of different ages, but it must be emphasized that more information is needed before positive conclusions can be drawn.

Significance of the Data

It is significant that the age of the zircon containing 4.6 ppm lead (52-C-10a-Z) is in close agreement with that of the zircon containing 127 ppm lead (52-C-8-Z). The introduction of only 1 ppm of foreign lead into the concentrate containing the smaller quantity of total lead would give an age of 84 million years, or an error of approximately 22 per cent. This indicates that the presence of original lead in the sample is negligible; otherwise a considerably greater age would have been obtained. Monazite is known to contain small amounts of original lead, approximately 1 to 3 per cent of the total lead. In the monazite sample containing 231 ppm of lead (52-C-8-M), the effect of original lead is negligible. The very close agreement of the monazite and zircon ages in one case and the rather close agreement in the other indicate the reliability of age determinations of monazite by this method. Monazite determinations seem particularly suitable for rocks containing zircon with less than 10 ppm lead and alpha activity of less than 100 α/mg/hr.

A worthwhile analogy can be drawn between the Boulder batholith and the pitchblende deposits of the Colorado Front Range. The pitchblende deposits are believed to have formed during the Laramide orogeny. Although generally assigned to the end of the Cretaceous, these deposits are believed by many geologists to be late Paleocene (Holmes, 1947, p. 140). On the basis of isotopically corrected lead and uranium ratios, Holmes (1947) has assigned an age of 58 million years to these deposits. The results obtained by the lead-alpha activity method on zircon and monazite from these batholiths show close agreement with age determinations by the lead-uranium method on bodies of about the same geologic age.

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NEUTRON-IRRADIATED QUARTZ AS A TRACER OF SAND MOVEMENTS*

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The Problem

Geologists have long felt the need for a tracer of sand movements in nature. Two classes of tracers have been employed with limited success. The first utilizes an external component added to the sand under study—*i.e.*, colored glasses or minerals not found in the environment under investigation. However, the size distributions, densities, and shapes of such tracers do not conform exactly to these properties in the natural components in the sand, and such characteristics determine the nature and amount of transport under the influence of fluid movement.

The second group of tracers utilizes natural components in the sand, such as rare minerals. In the relatively few environments in which techniques employing rare minerals can be applied, their use is limited to qualitative studies and is difficult to apply because it requires a detailed knowledge of the existing distribution of the trace mineral over the area to be studied. At best such tracers give information applicable only to particles of similar size, shape, and density, and thus do not apply to the major fractions of the sand. The treatment of a natural component to render it readily distinguishable has rarely been successful. The literature is replete with examples of dyed quartz, etched quartz, silvered quartz, etc. However, such tracers are usually either difficult to distinguish from the untreated grains, or the treatment is but temporal.

The natural tracer of sand movements should be: (1) of the same size distribution, density and shape as one of the major components under study, (2) easily and rapidly distinguishable from the sand mass, (3) available in relatively large amounts, (4) inexpensive, (5) able to retain its distinguishing properties over times comparable to the times of the fluid processes.

Since quartz is one of the dominant components of most sands, a method of tagging it should be highly desirable. Quartz can be concentrated from a sand by heavy-liquid, magnetic, electrostatic, or other separation techniques. Hence, quartz was subjected to slow neutron irradiation to ascertain if this treatment would bring about changes in the properties of the quartz such as induced radioactivity or color changes which would identify the quartz.

Experimental

Five-gram samples of quartz separated from the St. Peter sandstone were irradiated in the slow-neutron pile of the Oak Ridge National Laboratory for periods of 2 hours, 8 hours, 1 day, and 1 week under a rated flux of 10^{11} neutrons/cm^2/sec. Two weeks after removal from the pile the samples were assayed for their beta and gamma activities utilizing an end-window Geiger-Müller counter with a window thickness of 1.4 mg/cm^2.

From activity measurements for 2½ months the half-life of all samples was of the order of 15 days. In the sample subjected to an irradiation of 1 week, a longer-lived activity appeared during the second month. This latter activity was not identified. An aluminum absorption curve indicated a beta ray with a maximum energy of 1.6 Mev with essentially no gamma radiation present (less than ½ per cent of the total activity). From the above absorption and decay characteristics, the main activity is uniquely identified as phosphorus − 32. Turkevich and Samuels (1954) reported small amounts of P − 32 activity in similarly irradiated quartz.

The activity could not be removed by im-

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mersing the quartz grains in sea water and shaking the mixture for periods up to 2 weeks.

A slight color change toward buff was observed between the quartz irradiated for 1 week and the nonirradiated quartz. However, it was impossible to distinguish individual particles of irradiated from the nonirradiated quartz on the basis of color or any change in optical properties.

Tyler (1936) reported that apatite is the major inclusion in the St. Peter sandstone. More recently, Loewenstein (1954) pointed out that phosphates often accompany aluminum oxides in a twin substitution for the silicate tetrahedra. Microscopic examinations of the irradiated quartz were inconclusive with respect to apatite inclusions.

The phosphorus content of the St. Peter sandstone was determined spectrophotometrically as 250 parts per million by weight. Another value similarly determined for a sample of quartz sand from the barrier beach on Santa Rosa Island, Gulf Coast of Florida, was 620 parts per million by weight of phosphorus. Thus, quartz with phosphorus concentrations of these orders of magnitude can be readily irradiated to form a satisfactory tracer.

Sensitivity

Single grains of quartz with diameters or longest dimensions of approximately 0.1 mm were taken from the sample irradiated for 1 week and mixed with about a million inactive sand grains. The mixture was coated on an 8½ by 11-inch cellophane sheet which was moistened with thin lacquer. The cellophane, uncoated side down, was placed upon a sheet of Kodak "No-Screen" X-ray film for 4 days and then developed. The active grain was readily identified. Active grains were also identified in experiments with more than one irradiated grain per million inactive grains.

Discussion and Conclusion

Quartz containing phosphorus fulfills all the proposed qualifications for tracers. By increasing the irradiation time or using a higher irradiation flux, exposures of 1 or 2 days or less should be adequate to give recognizable darkening of the photographic paper. Experiments can be carried out over at least four half-lives (about 2 months) of the phosphorus. In the later part of such an extended period, longer exposures become necessary.

However, at this point health considerations enter. Although the half-life of the phosphorus is short enough to eliminate any large-scale contamination problems, it is of interest to consider the amounts of activity to be dealt with in hypothetical problems.

Assuming that detection of one grain in a million is possible, a well-sorted natural beach sand with an average particle diameter of 0.2 mm and a total porosity of 44 per cent could be traced if it contained approximately 10^5 irradiated quartz particles or 1.1 grams/cubic yard of sand. At Santa Barbara, California, where the littoral transport of beach sand, averaged over a 10-year period, is approximately 770 cubic yards per day (Johnson, 1953), 25.4 kg of irradiated quartz sand, if completely dispersed, would be sufficient to tag the sand transport past a point on the beach during a 30-day period.

Considering the sample that was irradiated for 1 week, we have 4000 counts per minute/0.10 g of sample at a counting geometry of 5 per cent. This is equivalent to 765,000 disintegrations per minute/gram or approximately ½ millicurie per kilogram or ½ curie/ton. In the example cited above, 13 millicuries would be necessary for a single experiment.

This amount of activity concentrated in one unit before dilution may constitute a health hazard. However, once diluted with about 50 or more parts of inactive material, no health hazard appears imminent. It is apparent that no danger will be encountered in experiments with smaller-scale natural phenomena, where lesser amounts of active material are required. These considerations assume a clean separation of the quartz from such minerals as feldspars and micas. The latter substances can contain elements such as potassium, sodium, and calcium which upon neutron irradiation give rise to high or long-lived activities.

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